RELIABILITY ASSESSMENT OF SMART DISTRIBUTION SYSTEM AND ANALYSIS OF AUTOMATIC LINE SWITCHES

By

Sudip Manandhar

Approved:

Nurhidajat Sisworahardjo
Assistant Professor of Electrical Engineering
(Thesis Advisor)

Ahmed Eltom
Assistant Professor of Electrical Engineering
(Committee member)

Abdul Ofoli
Assistant Professor of Electrical Engineering
(Committee member)

William H. Sutton
Dean, the College of Engineering and
Computer Sciences

A. Jerald Ainsworth
Dean, the Graduate School

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ABSTRACT

Electric Power reliability is a major concern of any utility company. Although the distribution system is getting advanced, reliable energy at a cheaper cost is still a big concern. Power utility companies are trying to provide reliable energy through many possible ways. One of the possible solutions is use of automatic switches.

Power utility companies are using automatic switch called IntelliRupter® for automatic fault detection, isolation and service restoration. It has been the biggest achievement in improving reliability so far. However, such automation is very costly. It needs proper planning for installation of such devices so that the utility company can make the most benefit at optimal cost.

The main objective of the study is to compute reliability of the distribution system using Failure Mode and Effect Analysis method. Also, it presents step by step economic analysis to determine optimum number and location of automatic switch fulfilling reliability and economic constraints.

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LIST OF ABBREVIATIONS

DOE, Department of Energy

ADA, Advanced Distribution Automation

SCADA, Supervisory Control and Data Acquisition

FDIR, Fault Detection, Isolation and Restoration

EPB, Electric Power Board

DA, Distribution feeder Automation

SAIFI, System Average Interruption Frequency Index

SAIDI, System Average Interruption Duration Index

CAIDI, Customer Average Interruption Duration Index

ASAI, Average Service Availability Index

ENS, Energy Not Supplied

MTTR, Mean Time To Repair

CT, Current Transformer

PT, Potential Transformer

NESC, National Electric Safety Code

Mph, Miles per hour

kV, kilovolt

IEEE, The Institute of Electrical and Electronics Engineers

UTC, University of Tennessee at Chattanooga

RTN, Return To Normal

CIC, Customer Interruption Cost

MBCA, Marginal Benefit to Cost Analysis

FMEA, Failure Mode and Effect Analysis

KW, Kilowatt

CMI, Customer Minute Interruption

DG, Distributed Generation

SEL, Schweitzer Engineering Laboratories

CI, Customer Interruption

NO, Normally Open

CB, Circuit Breaker

GA, Genetic Algorithm

CHAPTER I

INTRODUCTION

This chapter provides a brief introduction of Smart Grid and explains the importance of automation in the electrical distribution system. It also highlights how reliability can be improved by automation of the distribution system. Furthermore, it also emphasizes the ongoing ways to improve reliability of the distribution system through automation and how such automation should be done in order to be of the most benefit.

Smart Grid and Present Situation of the Distribution System

In the traditional distribution system, whenever there is power outage, the trouble call system is used to detect it. In other words, when a fault occurs and customers experience power outages, they report the power outage to the power utility company. The distribution system will then dispatch a maintenance crew to the field. The crew will at first locate the fault location and then implement the manual switching scheme to conduct fault isolation and power restoration. This conventional manual power restoration method might take several hours to complete, depending on how fast the customers report the power outage and how fast the maintenance crew can locate the fault point and restore power.

At present, the distribution system is shifting towards an intelligent network like Smart Grid. According to the U.S. Department of Energy (DOE), a Smart Grid is defined as an electricity network that can intelligently integrate the behavior and action of all users connected to it through communication, computational ability control and information technologies in order to enhance efficiency, reliability, economics and sustainability of electricity services. In other words, it is an electrical grid that is the integration of electric infrastructure and information technology. A Smart Grid is a present and future vision of the electric company which has characteristics, such as: (1) for radical improvement of the power system to minimize power outages (2) to enable and operate all generations and storage options (3) to enable new product services and markets (4) to optimize asset utilization and operate efficiently (5) to self heal disturbances (6) to operate resiliently against attack and natural disaster.

Concerning Smart Grid, Advanced Distribution Automation (ADA) is an important building block. ADA employs automation technology and digital control of electrical distribution systems to improve safety, reliability, and self-healing enablement as compared to a classic distribution system.

Any distribution system is evaluated based on its reliability. And the reliability is evaluated by reliability indices. Different reliability parameters are used in the distribution system in order to measure the system reliability. The objective of the study is to evaluate reliability of distribution system using reliability indices frequently used in the distribution system.

There are many factors that degrade the reliability of the distribution system. The ubiquitous reason is faults. There are various types of faults that commonly occur in the distribution system. Different protective devices are used in the distribution system in order to locate and isolate faults. Reliability of the distribution system is proportional to the average time taken to restore power. Hence, proper coordination between protective devices must be assured to speed the restoration process which will improve the reliability of the system significantly.

There are various methods to speed up the restoration process in order to improve the reliability of the distribution system. One of the methods is to use automatic switches. The power utility company is deploying feeder automatic switching devices like IntelliRupter® pulse closer which is a unique alternative to conventional automatic reclosers. Intellirupters provide self healing, automatic restoration as well as supervisory control and data acquisition (SCADA) functionality. These automated capabilities make implementation of fault detection, isolation and restoration (FDIR) faster.

Automation of the distribution network therefore significantly increases the reliability of the system by isolating a fault and reconfiguring the system in a very short period of time. However, the cost associated with the installation of the automatic switches is very high [1]. The installation of more automated devices will increase the cost tremendously. Therefore, proper planning must be done for the installation of such automatic switches so that the utility company can make a significant benefit. Usage of the optimal number of switches at optimum location of the distribution network can give a more reliable and economic system. However, the selection of an adequate number of manual and automatic switches and the optimal placement of them in the distribution networks is a difficult task [2]. The selection of the number of automated switches and their locations depends on the customers connected, reliability cost, installation and maintenance cost. Therefore, proper Economic analysis should be done which will take care of the reliability improvement by minimizing the customer interruption, the switches and the maintenance costs. The main objective of the economic analysis is to choose the best option fulfilling reliability and economic constraints.

Literature Review of Researches for Optimization of Automatic Switches

In the last decades, researchers have made several attempts to improve the reliability of a distribution system using optimal switch placement techniques. In [3], the reliability assessment of a distribution system is done on the basis of cost analysis. Two stage restoration (partial automation) is used and the objective is to minimize the cost due to energy not supplied (ENS). In [4], the immune algorithm (IA) is proposed to figure out the optimal placement of switching devices by minimizing customer interruption cost (CIC) and investment of line switches. The reliability index of each service zone is derived to solve energy not served (ENS), and then customer interruption cost is determined according to customer type and power consumption. Reference [5] uses the traditional reliability indices in order to derive the optimum location of automated switches in the distribution network. The calculation of reliability is presented, and the influence of automation on reliability is discussed in detail. Finally, the best configuration of the switches is derived using Genetic Algorithm (GA).

Despite the use of powerful simulation optimization tools, none of these proposals clearly signify the customer interruption cost. All of these proposals just account for the interruption cost resulting directly from power interruptions and relatively assign an easy dollar value. However, there are indirect impacts like damage to the system, hardware crashes, loss of sales and productivity, overtime pay, and relocating of businesses to areas with higher reliability. All of these costs resulting from direct and indirect impacts are considered in this research for the strong economic analysis.

In the proposed research, an efficient analytical method based on Failure Mode and Effect Analysis (FMEA) is used in order to determine the reliability parameters. The main objective is to minimize the system cost which is the sum of interruption cost and switch purchasing cost. Therefore a cost to benefit analysis is performed in order to choose the optimal placement of switches that will satisfy the reliability and economic constraints.

Overview of the Concept

Power utility companies are creating a comprehensive Smart Grid system in most of metropolitan areas of the United States. In these systems, most of power utility companies are deploying Intellirupters which provide information about switch open and closing time, faults location and durations, harmonics, transformer temperatures and oil chemistry. Intellirupters are also integrated to supervisory control and acquisition (SCADA) systems to employ technologies to transmit voltage, currents, power and phase angle. Utility companies thus have the capability to collect an ample amount of data generated by the sensing of operations of networks by Intellirupters.

As a part of the reliability study, a small electric distribution model provided by the power utility company will be selected and all required information such as feeder failure rate, load pattern, switch operation time and possible switch placement locations will be gathered. The selected distribution network will include a number of line switches which will sufficiently represent a larger network but small enough to manage the scope of the proposed study. An effective Failure Mode and Effect Analysis (FMEA) have been used for computation of reliability using a spreadsheet that can be applied to the electrical distribution system for high and economical efficiency. Reliability is evaluated using reliability indices, such as SAIFI, SAIDI, and CAIDI for all possible location of automatic switches.

After the reliability calculation, the economic analysis is performed for those options satisfying the reliability constraints. A cost to benefit method is used to determine optimal location of automatic line switches which has highest benefit to cost ratio.

Thesis Outline

The discussion of the study is organized as follows

Chapter Two presents the role of distribution automation to improve system reliability. The automation technique is discussed in detail with necessary diagrams.

Chapter Three explains about the reliability parameters used in distribution system with necessary formulas. It gives a brief concept of computing reliability indices with an example.

Chapter Four describes about the various factors that causes power interruption in distribution system. The chapter discusses briefly all of these factors and their impact on the distribution system reliability.

Chapter Five illustrates about the protective devices used in radial line protection and how their proper coordination will improve reliability of the distribution system. The coordination process is elaborated by using automatic sectionalizer called IntelliRupter®.

Chapter Six explains about the importance of economic analysis in the distribution system. This chapter details about customer reliability cost that need to be accounted for reliability assessment.

Chapter Seven details about the case study conducted for different type of feeders. The reliability of each model under partial and complete automation is calculated followed by economic analysis using benefit to cost analysis.

Chapter Eight discusses about the finding of case studies and direction for future research.

CHAPTER II

DISTRIBUTION AUTOMATION

This chapter explains the idea of distribution automation and the important role of automation in the distribution system in order to improve system reliability. The automation process is elaborated with the help of an example to understand the quick healing process to power interruption in order to provide a reliable, efficient supply to meet demands [3].

Objective of Feeder Automation

Distribution Automation generally refers to automation of the task that has to be done in a repetitive fashion over a period of time [5]. In other words, automation refers to distance supervision and control of substation equipment and feeder switches continuously in order to avoid power outages. Thus, the automation will improve reliability of the system by speeding up the service restoration process. The power companies are implementing numerous ways of improving reliability. In addition to supervisory control and data (SCADA) functions, replacing traditional manual switches with automatic switches can significantly improve reliability by reducing fault detection, isolation and service restoration time [6]. Automatic switches avoid the manual switching operations and have a significant role in saving maintenance cost as well as interruption cost. Therefore, concisely, the main objectives of feeder automation include but are not limited to

- Decrease the number of customer outages and duration of customer outages.
- Instantaneous fault detection, isolation and service restoration.
- Transformer and feeder load balancing.

Automation in Distribution Feeder Reconfiguration

In the radial distribution system, the fault current always flows from source to fault location. Therefore, in the properly coordinated automatic distribution system, the fault will be cleared by the nearest protecting devices. After the fault has been isolated, the system will reconfigure in order to restore power to its customers. The reconfiguration is done with the help of automatic and manual switches. The study mainly focuses on a two stage reconfiguration where a limited number of customers are restored quickly using automatic switches and the remaining customers are restored later using manual switching.

System reconfiguration usually takes place in two phases, upstream and downstream restoration. In the upstream restoration after the circuit breaker clears the fault, the fault is located and the nearest upstream switch is opened. This will restore power to all upstream customers.

In the downstream restoration, after the upstream reclosing switch is opened, the downstream sectionalizing switch close to the fault location is opened. This will allow the normally open switch to close, restoring service to downstream customers. The overall two stage reconfiguration process is elaborated in the next section with a diagram.

Explanation of a Two Stage Automatic Feeder Reconfiguration

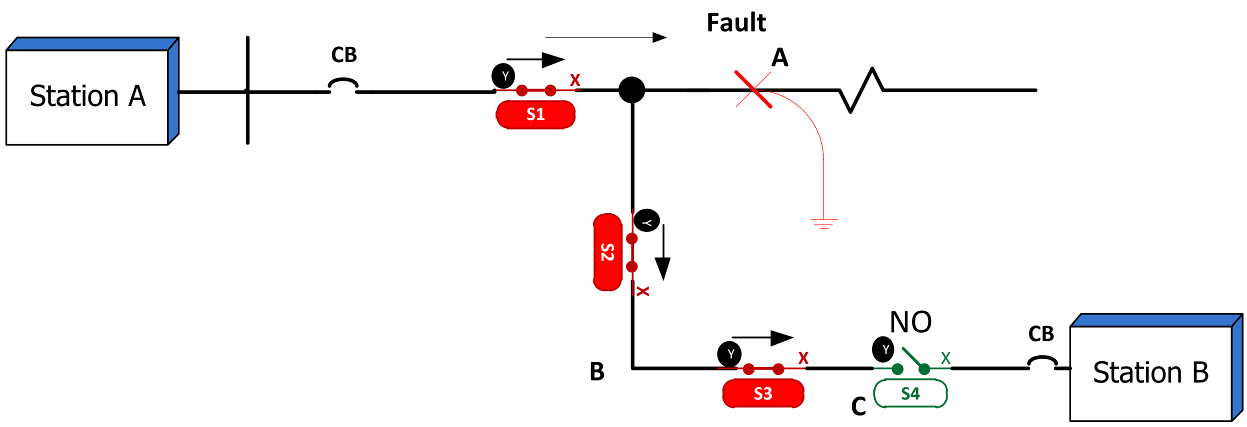

Figure 2.1 Upstream and Downstream Protection in Power System

In Figure 2.1, assume normally closed switches S1 and S2 are manual while S3 is automatic. It is normal practice of the power company to make normally open (NO) switches automatic. When the fault occurs at point A, the circuit breaker at the substation will trip and interrupts all customers in feeder A, B and C. However, since switch S3 is automatic, it will open itself in a few seconds and will let normally open (NO) automatic switch S4 close restoring customers in segment C in a few seconds. After the fault has been located, the dispatch crew will open switch S1 and S2 through remote operation using SCADA in order to isolate the fault. This will restore power to upstream customers of switch S1 in feeder A. In downstream restoration, after the dispatcher opens switch S2, then switch S3 will close and power is restored to all customers in feeder B and C. The restoration time of loads A and B is longer than automatic switching and will depend on how long it takes for the dispatcher to locate and isolate the fault. Therefore, with an increase in the number of automatic switches, the reliability of the distribution system will increase significantly. However, it is important to have an idea about what reliability actually means and ways to evaluate it in order to take proper corrective measures. The next chapter will discuss more in detail about the distribution system reliability and its methods of evaluation in the practical world.

CHAPTER III

DISTRIBUTION SYSTEM RELIABILITY

In this chapter a brief overview about the reliability and the reliability parameters used frequently in the electrical distribution system is presented. The reliability indices such as SAIFI, SAIDI, CAIDI and ASAI frequently used by power utility companies to evaluate reliability of the distribution system are discussed with respective formulae. At the end of the chapter, an example is provided which fully details the calculation of reliability parameters in the distribution system.

Overview of Reliability

Distribution reliability primarily means continuation of power supply without interruption. IEEE 1366 standard defines distribution reliability as measurement of keeping lights on [7]. Simply, reliability is the measurement of equipment outage rates and power interruption duration. There are various events that disrupt normal operation of the distribution system leading to power outages. However, some key descriptions pertaining to distribution system reliability are explained below.

Faults

Faults are characterized by an enormous current flowing in the circuit in an abnormal way and can cause equipment insulation failure leading to power outages [7]. In the distribution system, normally there are two types of faults, temporary and sustained [8]. Temporary faults clear themselves in a short time once after the path is de-energized and customers will see a momentary interruption [7]. A permanent fault remains for long time and needs manual switching to clear it.

Temporary or Momentary Interruptions

According to IEEE 1366 standard, faults lasting less than 5 minutes are categorized as momentary interruptions [7], [8]. Most momentary faults may not necessarily lead to a power outage. For example, the falling of a tree branch on power lines may not lead to a fault. Besides faults, the operation of automatic switches also results in momentary interruption. The study doesn't account for momentary interruptions as most utility companies do not consider a momentary interruption in a reliability study due to the difficulty knowing when it happened.

Sustained or Permanent Interruptions

Sustained interruptions occur when customers are out of power for a long time. IEEE 1366 standard classifies faults lasting more than 5 minutes as sustained faults [7] [8]. Sustained faults are generally characterized by open circuits and will result in power outage.

Reliability Indices

Reliability indices are simply statistical aggregations of reliability data of well defined loads, equipment and power users [7]. The electrical distribution system is basically analyzed based on its reliability and reliability can be evaluated using reliability indices [3]. In the distribution system, the reliability is basically represented by load based indices and overall system based indices.

Load Based Indices

Load based indices are conventional indices which typically represent the data of each connected individual customer. The load point indices used in this thesis are represented below.

- Average failure rate, λ (f/yr)

$$\lambda_i = \lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_m = \sum_{j=1}^{n} \lambda_j \tag{3.1}$$

Where,

n = total number of customers at load point i
λ_j = average failure rate of loads at point i
λ_i = average failure rate of load point i

- Average outage time, r (hr)

$$r_i = \frac{(r_{i1}\lambda_1 + r_{i2}\lambda_2 + r_{i3}\lambda_3 + \cdots + r_{im}\lambda_m)}{\lambda_i} = \sum_{i,j=1}^{n} \frac{r_{i,j}\lambda_j}{\lambda_i} \tag{3.2}$$

Where,

n = total number of feeders at load point i
$r_{i\,j}$ = average outage time of feeder j due to failure of segment i
λ_i = average failure rate of each segment i

- Average annual outage time, U (hr/yr)

$$U_i = r_i\lambda_i \tag{3.3}$$

Where,

U_i= average annual outage time

System Based Indices

System based indices are most widely used indices by utility companies for the reliability improvement targets. In other words, system based indices often serve as benchmarks for reliability improvement. The main advantage of system based indices is that it treats all type of customers equally despite its size [7]. Some commonly used system indices are described below.

System Average Interruption Frequency Index

System Average Interruption Frequency Index (SAIFI) represents the total number of sustained interruptions in a system over a year [9]. It is the ratio of the total mean failure rate of each element and the total customers served in the system. Total mean failure rate for an element is the total number of interruptions that a customer on that segment is expected to experience in a year [10]. SAIFI can be reduced by reducing the number of sustained interruptions.

$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{n} \lambda_i \mathrm{N}_i}{\mathrm{N}} \tag{3.4}$$

Where,

n = total number of load points
λ_i = average failure rate of each segment i
N_i = Number of customer interrupted
N = Total number of customers served

System Average Interruption Duration Index

System Average Interruption Duration Index (SAIDI) is the annual outage duration an average customer will experience over a year [7]. The sum of the annual outage duration represents the total number of annual customer hours interrupted due to all possible faults.

SAIDI can be reduced by reducing the number of interruptions or by reducing the duration of interruptions.

$$\text{SAIDI} = \frac{\sum_{i=1}^{n} U_i \text{N}_i}{\text{N}} = \frac{\sum \text{Customers minutes Interrupted (CMI)}}{\text{Number of customers served}} \qquad (3.5)$$

Where,
n= total number of load points
U_i = average annual outage rate of component i
N_i = number of customers disconnected
N = Total number of customer served

Customer Average Interruption Duration Index

Customer Average Interruption Duration Index (CAIDI) is the measure of the average time to restore service to customers per interruption. CAIDI can be improved by increasing the number of momentary interruptions or decreasing the duration of sustained interruptions. Due to this, CAIDI might not be that useful to describe reliability as compared to SAIDI and SAIFI. Customer Average Interruption Duration Index is calculated as

$$\text{CAIDI} = \frac{\text{Sum of all customers interruption durations}}{\text{Total number of customer interruptions}} = \frac{\text{SAIDI}}{\text{SAIFI}} \qquad (3.6)$$

Average Service Availability Index

Average Service Availability Index (ASAI) provides the same information as SAIDI and represents the customer weighted availability of system over a year. Usually ASAI has a value of more than 0.999.

$$\text{ASAI} = \frac{\sum_{I=1}^{N}(N_i * 8760) - \sum_{i=1}^{N}(U_i N_i)}{\sum_{I=1}^{N}(N_i * 8760)} \qquad (3.7)$$

Where,
U_i = average annual outage rate of component i
N_i = number of customers disconnected
N = Total number of customer served

Example for Calculation of Reliability Indices

Consider the simple one line diagram of a large Commercial feeder as shown in figure 3.1. The total number of customers connected is 60 and the average load served is 5000 KW. Assume there are no protective devices and alternative sources in this circuit.

The necessary network data of feeder is shown in table 3.1.

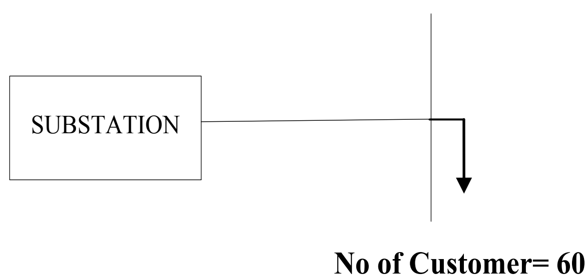

Figure 3.1 Distribution Model Reliability Indices Calculation

Table 3.1 Network Data of the Feeder

Components	Avg failure λ(f/yr)	MTTR (hr)
Substation	0.10	0.5
Line	0.15	2.0

In this example, 60 customers are connected to a substation through an overhead line. Any fault at the substation or overhead line will interrupt the supply to 60 customers as there are no protection devices in this circuit.

Customer Interruption= Avg. failure rate (λ) * Number of customer (N) (3.8)

a) The calculation of SAIFI is shown below.

Table 3.2 Calculation of SAIFI

Components	Avg failure λ(f/yr)	MTTR (hr)	Number of Customers	Customer Interruption
Substation	0.10	0.5	60	6
Line	0.15	2.0	60	9
		Total		15

Total customer Interruptions=15

Total customers connected=60

Then,

$$\text{SAIFI} = \frac{\text{Total Customer Interruption}}{\text{Total Cusomers Connected}} = \frac{15}{60} = 0.25$$

b) For calculation of SAIDI, we have to take account of the mean time to repair (MTTR) each fault component. As a result we get the total duration to repair a fault.

Table 3.3 Calculation of SAIDI

Components	Avg failure λ (f/yr)	MTTR (hr)	Number of Customers	Customers hour interruption per year
Substation	0.10	0.5	60	3
Line	0.15	2.0	60	18
		Total		**21**

Customers hour interruption/year= failure rate (λ)*MTTR*No. of customer interrupted (3.9)

Then,

$$\text{SAIDI} = \frac{\text{Customers hour interruption/yr}}{\text{Total customers}} = \frac{21}{60} = 0.35$$

c) CAIDI= $\frac{\text{SAIDI}}{\text{SAIFI}} = \frac{0.35}{0.25} = 1.4$

d) ASAI = 0.99996

CHAPTER IV

INTERRUPTION FACTORS

There are various factors that cause interruption in the electrical distribution systems. Equipment failures, animals, human errors, natural disasters are some of the frequently occurring factors leading to power interruption. Distribution lines are vulnerable to these failure factors and their reliability is always a question. A brief discussion on each of these failure factors and their effects on reliability of the electrical distribution system are presented in this section.

Equipment Failures

Equipment failure is one of the top reasons for power interruption in the distribution system. Transformers, circuit breakers, overhead lines, switches and insulators are some examples of electrical equipment's installed in the distribution system. All of these equipment's have their own probability of failure. In order to decrease rate of failure, proper installation and timely maintenance of this equipment is highly recommended.

Failure of transformers in a substation due to various faults can cause interruption of service to hundreds of customers. During this interruption, another healthy transformer is called upon to carry this load which risks this transformer being overloaded. This might lead to failures of transformers due to overloading leading to power interruption to thousands of customers. Proper decision should be made to determine whether to overload transformers or not. Overloading causes heating in transformers which decreases its thermal age.

Circuit breakers are other devices which cause frequent interruptions due to untimely co-ordination. Proper setting and maintenance is required for the healthy action of circuit breakers. Otherwise, there might be cases in which circuit breakers malfunction or fail to operate when they should [11]. Usually circuit breakers are timely coordinated with other protective devices using relays. Untimely co-ordinations can be reduced by testing settings, relays, CT/PT ratios and wiring [11].

Human Factors

There are many ways in which a human can cause interruption in the distribution system. These interruptions can be categorized into scheduled or unscheduled. Scheduled interruption occurs when part of the radial distribution system has to have maintenance or be upgraded. The utility company notifies its customers in advance prior to maintenance. During maintenance, it might require equipment to be de-energized and all the customers downstream of that equipment will be interrupted. Even when fed by an alternative source, these customers experience momentary interruption due to switching after de-energizing the circuit.

Unscheduled interruption may occur due to human error, vehicle accident or vandalism. One example is accidently operating wrong manual switch. Other errors include the falling of tree branches while trimming trees. Also, vehicle accidents can cause a significant impact on failure rates of distribution lines. Most road mishaps can cause damage to the poles bringing power lines to the ground. Using fences or crash resistant poles may reduce the impact of automotive interruptions.

Animals

Animals are another large cause of interruption in the electric system [11]. Animals, like snakes, squirrels, birds and rats can cause problems and hence, impact the reliability of the electrical distribution system. Squirrels are the most common reliability concern for the utility company in wooden areas. Squirrels bring grounded equipment in contact with phase conductors causing faults. Special plastic guards are required to ensure protection of conductors.

Birds are another cause of faults in the electrical distribution systems. They cause faults in systems by bridging the conductors with their wings. To prevent roosting, protective anti-roosting structures, like cones structures, should be placed on top of poles [11].

Snakes, being cold blooded animals, tend to squeeze through holes and stay in warm places like cabinets and substations. Snakes cause problems by bridging two conductors. Electrical cabinets should be sealed and food remains should be removed.

Large animals like cows, horses and bears can cause damage to poles by rubbing on guy wires. Guy wires provide stability to the poles against tension caused by power lines [12]. A lot of cattle lean on or rub on poles or guy wires making poles lean and this reduces the reliability as the chances of collapsing poles increase. Fences can be built around the poles in order to increase reliability.

Extreme Weather

Extreme weather has significant impact on reliability. It causes more outages in the electrical distribution system. Extreme wind with high velocities, like tornadoes and hurricanes, can blow off poles and distribution conductors causing damage to many devices in the meantime. The falling of towers in a cascading way, due to one pole being knocked off by wind, is one of the catastrophic examples. Severe weather includes wind, lightning, tornadoes, hurricanes, ice storms and fires.

Extreme winds refer to a huge gust of linear winds that blow down trees and poles. In the United States, different states experience different wind speed due to their geographical shapes and temperature gradient. Therefore, the National Electric Safety Code (NESC) established a policy according to which a structure must be able to withstand the ice loading and wind (section 3.3.6).

Tornadoes are concentrated rotating masses of air having destructive high magnitudes. Tornadoes are measured in Fujita scale. According to this scale, tornadoes are ranked into F0 (0-72 mph), F1 (73-112 mph), F2 (113-157 mph), F3 (158-206 mph), F4 (207-260 mph), F5 (261-318 mph) categories [11].

Hurricanes can cause severe damage to the distribution system, too. Hurricanes cause damage by blowing down trees and poles. This can result in broken conductors, broken poles, and broken cross arms. Damages can also result due to flying tree branches, poles and metal sheets. After a hurricane, huge debris is left and can cover electrical equipment which during cleaning can be damaged by cleaning vehicles.

The swinging of the line conductor can cause faults when they touch each other. Therefore, to reduce interruption due to swinging, enough gaps must be maintained between conductors by increasing the span length of transmission poles.

Lightning storms cause significant damage to tall structures like metal poles and transmission lines. Ground cables and surge arresters should be mounted on top of poles in order to protect these lines.

Ice storms increase intensive stress on conductors as they start to accumulate ice causing the sagging of conductors. This will increase the probability of fault due to the breaking of the conductor due to the weight of ice and blowout due to the conductors coming in contact with each other.

Fires can cause significant damage to the distribution lines. Power conductors start to anneal and lose its electrical, as well as mechanical, strength due to fires. Different distribution conductors are mounted on wooden poles which are susceptible to fire and they may fall down due to the loss of mechanical strength due to the heat. If fire catches wooden poles and reaches the top of poles, it may damage line conductors as well as electrical instruments, like IntelliRupter®, transformers, recloser etc.

Trees

Trees may cause interruption in the distribution system. Due to the falling of trees, overhead conductors may receive mechanical damage. Also, the growing of branches can push conductors together and need to be trimmed. Also, animals like squirrels and rats use trees as their gateway to electrical poles.

Therefore, in order to mitigate the effect of these failure factors on the reliability of the distribution system, proper protective devices such as relays, circuit breakers, and automatic switches must be installed. The next section details about the protection devices used in this study and role of proper synchronization between these devices in improving reliability of the electrical distribution system.

CHAPTER V

POWER SYSTEM PROTECTION

Power system protection is the backbone and effective way to improve reliability of the distribution system. This section describes various protection devices used for radial line protection. Proper coordination between these protecting devices must be assured in order to reduce the number of customer interruptions during a fault which will improve reliability of the distribution system.

Protective Devices

Different types of protection devices like reclosers, relays, switchgears and automatic sectionalizers are used in overhead line protection of the electrical distribution system. All of these devices are explained in addition to newly introduced automatic sectionalizer called IntelliRupter®.

Relays

Protective relays generally receive information from devices like CT (current transformer) and PT (potential transformer) and then send signals to the circuit breaker to open when a fault occurs. Depending on the type of protection, relays can be set to protect from fault currents. For example, the overcurrent relay sends a trip signal when it senses a higher current than normal value. Instantaneous relay trips instantaneously when a fault occurs, whereas time overcurrent relay trips with time delay in order to coordinate with other protecting devices.

Figure 5.1 SEL Relay [13]

High Voltage Circuit Breakers

High voltage circuit breakers usually interrupt high fault currents. The insulating mediums that are usually used in the circuit breakers are vacuum, SF6 (sulfur hexafluoride gas) and oil.

Figure 5.2 Circuit Breaker [14]

Reclosers

A recloser is a device which has the capability to sense and interrupt fault currents as well as re-close automatically in an attempt to re-energize a line [15]. This device works similar to a circuit breaker with relay and has instantaneous as well as delayed protection schemes. This device is more cost effective as compared to a circuit breaker with relay but has less interrupting capability [15].

Figure 5.3 Recloser [16]

Switchgears

Switchgear is a combination of fuses or circuit breakers which have a tendency to isolate a fault and de-energize the circuit [17]. Once a faulted current has been broken, switchgears can be opened or closed manually until the faulted segment is repaired. The switchgears should have the ability to quench the arc created during opening of the circuit, but Switchgears have no ability to change the number of interruptions experienced by utility customers [18].

Automatic Sectionalizers

Automatic sectionalizers automatically de-energize a faulted section so that non-faulted line sections can be safely energized. It helps to overcome the coordination problems of other protection devices like fuse and reclosers near substations. When the fault current exceeds the pre-set value, the sectionalizer will open instantaneously in order to isolate the fault to restore power back to unfaulted line segment customers. This also helps to save the fuse from blowing which is also known as a "fuse saving" scheme.

IntelliRupter®

Intellirupter is an advanced pulseCloser which has the ability to work in stand-alone mode as the fault interrupter and also can be integrated in the SCADA system for automatic restoration in the distribution system [19]. Pulsecloser means that it tests fault with a pulse instead of huge fault current. Intellirupters provide a significant protection for 60-Hz systems through 38 KV and 50-Hz systems through 24 KV [19].

Figure 5.4 Non Disconnect Style 38 kV Intellirupter [19]

Intellirupters also have inbuilt components like sensors, control group, surge arresters, power control and disconnectors in addition to a Wi-Fi transceiver which provides point to point wireless communication under IEEE 802.11b standard [19]. We can open and close Intellirupters, set hot-line tags and change protection profiles by establishing a secure Wi-Fi connection using a laptop from a distance up to 150 feet. For a remote operation, it can be integrated into the SCADA system [19].

Figure 5.5 Configuring Intellirupter Control profile Using WiFi Communication Link [19]

Advantages of Intellirupters over Reclosers

There are significant benefits of Intellirupters over conventional reclosers which are discussed below.

1. Intellirupters do not stress the system with a high magnitude of fault current every time it makes an attempt to reclose into a fault. IntelliRupters pulse closes smartly after testing for fault current before closing [19].
2. Intellirupters detect faults, isolate and restore power in seconds.
3. With Intellirupters, the system only experiences over current stress from the initial fault, not from reclosing application [19].
4. No co-ordination technique is required as compared to conventional reclosers. Series Intellirupters can be set in such a way that after one unit upstream opens to isolate the fault, those downstream can operate at the same time, too [19].

Distribution Automation Using Intellirupter

Figure 5.6 below shows an example of distribution automation using Intellirupters. In this radial network, TBC03, TBC08, TBC10 and TBC14 are normally open automatic switches and the rest are all normally closed. Each substation is equipped with a circuit breaker capable of interrupting high fault current.

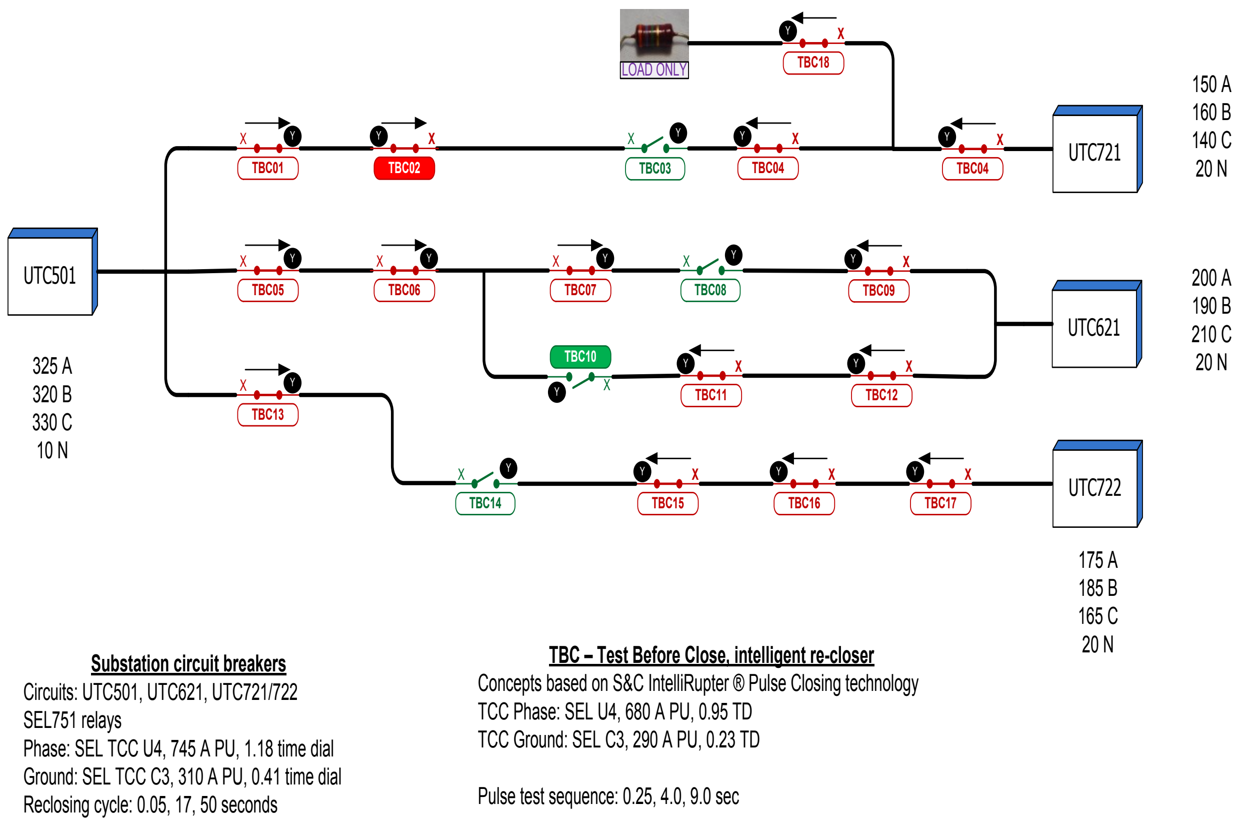

Figure 5.6 A 12 KV Feeder at Normal Condition

Assume a fault occurs between TBC05 and TBC06, TBCO5 detects fault and trips open instantaneously before UTC501 relay operates. After 0.25 seconds, first pulse test is made. If the fault persists, the switch TBC05 will open. The second pulse test is made after 4 seconds. If the fault still remains, it will open again. The final pulse test is made after 9 seconds. If the fault still is not cleared, then a switch TBC05 gets locked out. In order words, no reclosing attempts are made further. TBC05 sends an open request to switch TBC06 to isolate the fault. TBC06 accepts the open request and confirms open back to TBCO5. TBC05 then sends a find alternate source message to TBCO8 and TBC10. TBC10 agrees to close and TBCO8 stands by. After Team TBC06/TBC07 agree to let TBC10 close, TBC10 pulse tests into the de-energized section. If no fault is detected, TBC10 closes. TBC06-Y, TBC07-X & Y and TBC08-X detect a good source. Figure 5.7 shows the circuit diagram after Intellirupters have isolated the fault between TBC05 and TBC06.

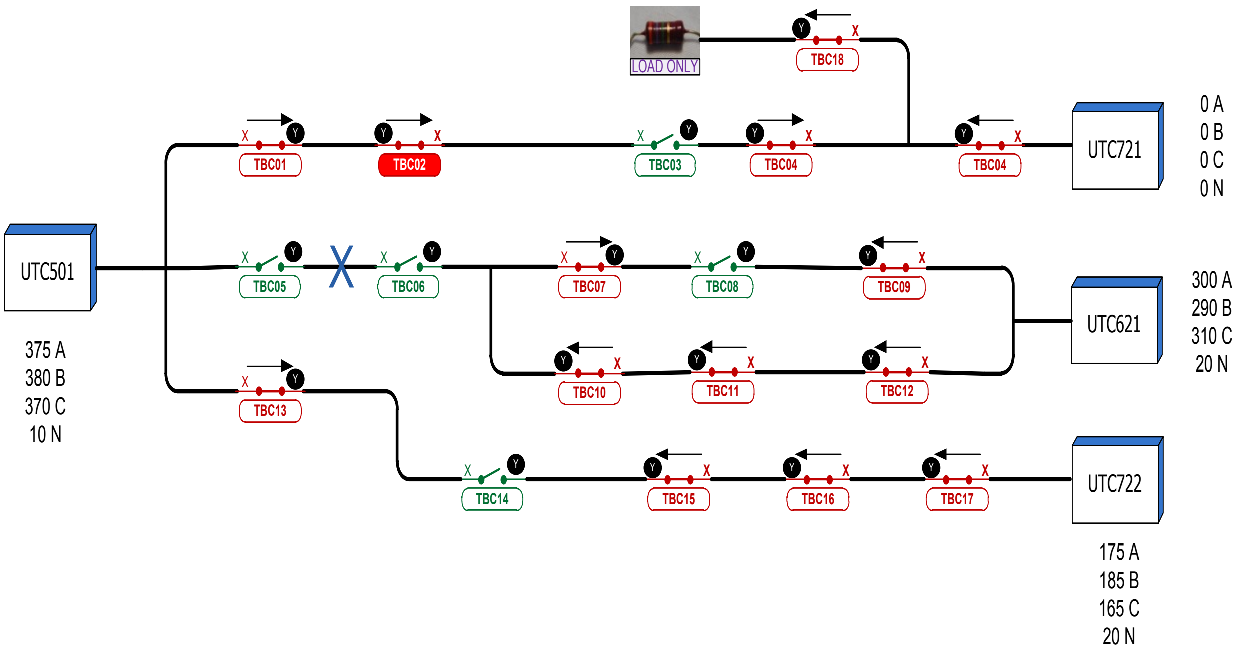

Figure 5.7 A 12 kV Feeder Model after Fault Isolation

After the fault has been cleared, the circuit is put back the way it was before the fault. Once line Personnel finishes manual repair, the dispatcher issues a close command to TBC05. TBC05 first pulse tests into the faulted section. If it is not faulted, TBC05 closes. Return timer starts for 5 minutes. After return timer expires and TBC05 detects no fault, it sends a close signal to TBC06. TBC06 pulse closes into the line and once it confirms the line is unfaulted, it confirms a close signal back to TBC05. TBC06 then allows TBC10 to open and the system is back to normal.

The fast fault healing capacity of Intellirupters has made it biggest achievement in the field of reliability improvement of the electric distribution system. However, these automatic sectionalizers are very expensive. Proper economic analysis is necessary to compare the benefit made from these switches with respect to their cost.

CHAPTER VI

ECONOMIC ANALYSIS

It costs money for the utility company to improve reliability of the distribution system [7]. The utility company will be willing to invest to improve reliability if there is a significant benefit. Therefore, economic analysis becomes one of the vital tools for reliability assessment. Reliability engineers use various analysis methods in such a way in order to maximize performance and reliability by investing in a cost effective way. In this research, marginal benefit to cost analysis is used for economic analysis.

Objective of Economic Analysis

The main objective of any system is to be both reliable and cost effective [3]. Automation of the distribution network will significantly increase the reliability of the system by decreasing outage time. However, the cost associated with the installation of the automatic switches is quite expensive [1]. Therefore, the usage of the optimum number of switches placed at the most probable areas of the distribution network can give us a more reliable and economic system. The selection of the number of automated switches and their locations depends on the total reliability cost.

Figure 6.1 illustrates the ideal relationship between the system reliability and the costs with respect to the customer interruption and utility cost. The total reliability cost is the sum of the costs to the utility and its customers. Utility costs are the function of reliability [7]. That means the utility must spend some amount of money on protection upgrade, automation, system reinforcement and maintenance to improve the reliability. As reliability increases, the customer interruption cost decreases; however, it will significantly increase the utility cost of installing automatic switches. Hence, the optimal cost has to be found where minimizing the total cost maximizes the economic cost to society. The minimum point of this curve is where total utility cost and interruption cost intersect each other. Most utility companies do not want to operate beyond this minimum point unless they have considerable benefit.

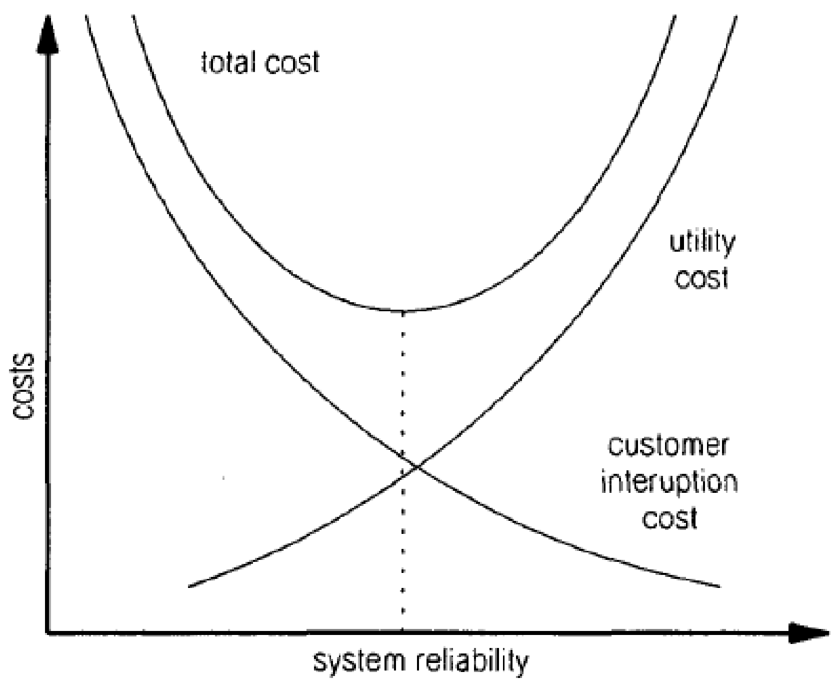

Figure 6.1 Optimization Curve for Reliability Costs [20]

The Problem Formulation

Therefore, the main objective is to find the optimum number and location of sectionalizing switches in order to minimize the customer interruption cost, investment cost of line switches and maintenance cost. Hence, the problem can be expressed as follows [1].

$$\text{Minimize Cost} = \text{Customer Interruption Cost} + \sum \text{Switch cost} + \sum \text{Maintenance cost} \qquad (6.1)$$

Subject to constraints,

- Reliability parameters (SAIDI, SAIFI)
- Approved Budget
- Switch locations
- Geography

Customer Interruption Cost (CIC)

Customer Interruption Costs are simply revenues lost by the utility companies due to power interruption to the connected customers. These revenues may be in the form of system failure, ruined process, overtime pay and lost productions. The customer interruption cost varies from residential to industrial customers. For the residential customer, interruption cost may be really small as compared to commercial and industrial customers. In addition, interruption cost also depends on the duration of the interruption, the time of the week and whether customers are informed about the interruption ahead or not. The customer having a good back up of power system is supposedly impacted less.

Customer Interruption Cost can be formulated as [1],

$$\text{CIC} = \sum_{j=1}^{N} \sum_{k=1}^{NLP} \lambda_j C_{jk}(r_j) L_k \tag{6.2}$$

Where,

N = Number of total feeder segments

NLP = Number of load points isolated due to fault in segment j

λ_j = Failure rate of segment j

$C_{jk}(r_j)$ = outage cost ($/KW) of load k due to fault in segment j with an outage duration of r_j

L_k = Average load at point k (KW)

Table 6.1 shows the estimated average electric customer interruption per event according to a survey conducted by the University of California, Berkeley. The interruption cost for 1 hour interruption is provided for residential, commercial and industrial loads.

Table 6.1 Estimated Average Electric Interruption Cost per Event US 2008$ by Customer Type, Duration and Time of Day [8]

Interruption Cost	Interruption Duration				
	Momentary	30 minutes	1 hour	4 hours	8 hours
Medium and Large C&I					
Morning	$8,133	$11,035	$14,488	$43,954	$70,190
Afternoon	$11,758	$15,709	$20,360	$59,188	$93,890
Evening	$9,276	$12,844	$17,162	$55,278	$89,145
small C & I					
Morning	$346	$492	$673	$2,389	$4,348
Afternoon	$439	$610	$818	$2,696	$4,768
Evening	$199	$299	$431	$1,881	$3,734
Residential					
Morning	$3.70	$4.40	$5.20	$9.90	$13.60
Afternoon	$2.70	$3.30	$3.90	$7.80	$10.70
Evening	$2.40	$3.00	$3.70	$8.40	$11.90

Table 6.2 Average Energy Consumption by Customer Type [8]

Sector	Annual KWh
Medium and Large C&I	7,140,501
Small C&I	19,214
Residential	13,351

Marginal Benefit to Cost Analysis

Marginal benefit to cost analysis is an effective tool for power utilities to improve reliability of the system while minimizing cost. Every power utility companies have a fixed budget every year for reliability improvement. The utility company has to assure that each dollar spent to improve reliability gives them maximum benefit. Marginal benefit to cost analysis helps the utility managers and distribution reliability engineers to decide how to spend this budget in the most effective manner.

Marginal benefit to cost analysis states that every dollar will be spent one at a time with each dollar funding the project that will result in the most reliability benefit, resulting in an optimal budget allocation that identifies the projects that should be funded and the level of funding for each [21].

In marginal benefit to cost analysis, the system will be upgraded until the desired reliability parameters are met or the allocated budget becomes insufficient. The following algorithm is used for marginal to cost benefit analysis.

1. Identify all possible upgrade options for the system.
2. Calculate the cost and benefit of all projects.
3. Set up the starting point.
4. Compute the $\Delta B/\Delta C$ ratio for all upgrades.
5. Identify an upgrade that has the highest $\Delta B/\Delta C$ that is within the budget constraints and reliability requirements

CHAPTER VII

CASE STUDIES AND RESULTS

In this section, a prototype 12 kV radial feeder commonly used in the distribution network is studied under different line loading and the number of customers. The reliability of each model under partial and complete automation is calculated and benefit to cost analysis of each model is carried out in order to find the optimum location of switches that satisfies reliability and economic constraints.

Methodology

Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) is an analytical inductive technique that accounts for the possible failure mode of the system and their impact on reliability of the distribution system. For each component the failure mode and resulting impact on the system is recorded in the worksheet. This method is often used in the system reliability study. A successful FMEA helps to identify each failure mode, probability of occurrence of each failure mode, and necessary actions required to mitigate such failure modes.

The steps followed in FMEA are listed as follows:

1. Identify all failure modes.
2. Figure out their probability of occurrence λ.
3. Select a contingency and its impact on all loads.

4. Weigh the impact of contingency by multiplying with λ.
5. Follow the previous steps to the rest of all contingencies.
6. Sum the contribution of all individual contingencies.

Reliability worth Assessment

The vital step in reliability assessment is to carry out a reliability study and to calculate the set of reliability indices [20]. For computing reliability parameters, the subsequent steps are followed.

1. The number and possible placement of the switches, load points, and line segments.
2. Average failure rates of each segment and load lines.
3. The number of customers connected and the average consumption of each load.
4. The average repair time of automatic or manual switches.
5. Get feeder topology and switch locations.
6. Identify switches to operate to isolate faults.
7. Total switch operation time.
8. Identify loads affected by feeder outage.
9. Compute number of customers with power outage.
10. Calculate reliability parameters (SAIFI, SAIDI) and interruption costs.

Case Studies

Case I: A 12 kV Parallel Residential Feeder

Consider a 12 kV residential feeder having the majority of the residential load is shown in Figure 7.1.

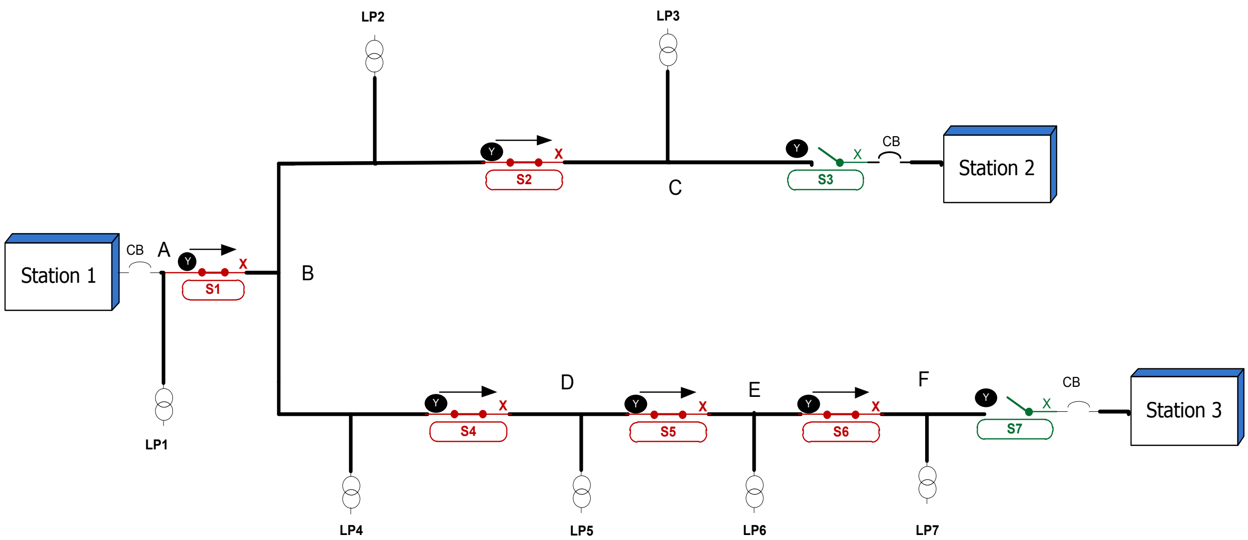

Figure 7.1 12 kV Radial Feeder Model

In this model, all the loads are fed by the substation 1. Two alternative sources are available for the back-up supply at the end of each node through normally open switches S3 and S7. It is the normal practice of utility companies to make normally open switches automatic. S1, S2, S4, S5 and S6 are the possible location for placement of normally closed automatic switches.

Step I: Gather all the necessary data. Table 7.1 shows the network data of the feeder. The load location and their individual consumption are shown in Table 7.2. Load point 7 is a commercial load of 450 kW.

Table 7.1 Network Data of the Residential Feeder

Failure Mode	Failure Rate (λ)	Total Length(miles)
A	0.15	4
B	0.15	4
C	0.15	4
D	0.15	4
E	0.15	4
F	0.15	4

Table 7.2 Load Data of the Residential Feeder

Load Point	Average No. of Customers	Average Load (KW)
1	133	900
2	100	850
3	133	900
4	100	890
5	133	900
6	133	700
7	10	450

Step II: Reliability Analysis

For reliability analysis, certain assumptions made in this thesis are mentioned below.

- The system is radial.
- All the faults are sustained.
- The mean time to repair each of these feeder faults is assumed to be 2 hours.
- The automatic switching time is 5 seconds.
- The manual switching time is 1 hour.

The method of finding reliability parameters with different numbers of automatic switches in a distribution system is a “combinatorial process”. Appendix A.7 lists the reliability indices of the system for all possible placements of normally closed automatic switches. Table 7.3 lists the best value of reliability for the switch configuration with respective numbers of normally closed automatic switches. 'A' stands for automatic switch and 'M' for manual switch.

Table 7.3 Reliability Indices for number of Automatic Switches in the Residential Feeder

No. of Automatic Switch	Switch Configuration	SAIFI	SAIDI	CMI
0	MMAMMMA	0.89	58.12	43128
1	MMAAMMA	0.44	36.32	26955
2	AMAAMMA	0.32	26.23	19467
3	AAAAMMA	0.25	19.37	14373
4	AAAAAMA	0.17	14.53	10782
5	AAAAAAA	0.14	14.53	10782

As automation increased, the reliability parameters (SAIFI, SAIDI and CMI) significantly improved. This is due to a decrease in rate of power outage time. However, automation increased reliability of the system to some point. After that point, there is no significant benefit of automation as the reliability saturates. Figure 7.3 shows that the plot of SAIFI and SAIDI improve as a result of an increase in automatic switches.

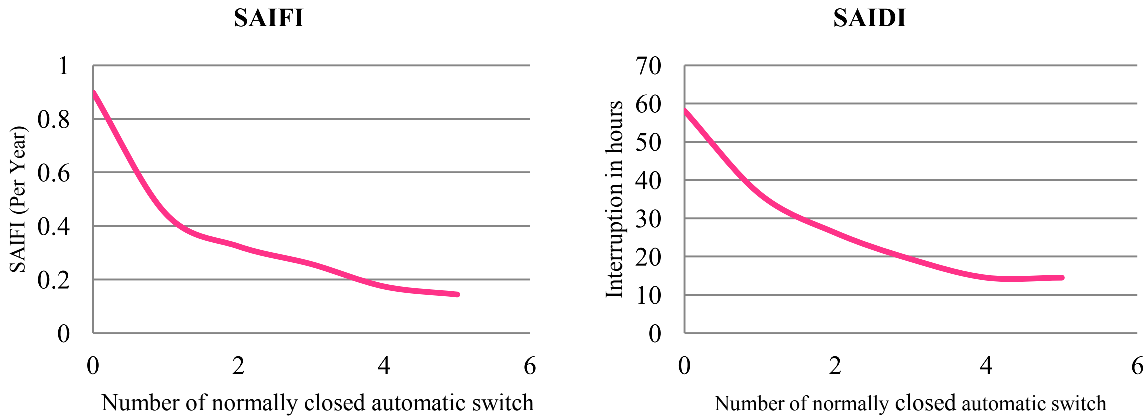

Figure 7.2 SAIFI and SAIDI Diagrams for 12 kV Residential Feeder

Step III: Economic Analysis

Even though reliability improved and saturated at some point, the number of automatic switches after which saturation occurred might or might not be the optimal point. Proper economic analysis must be done in order to figure out the optimal switch number and reliability that can be achieved within a given budget. A proper benefit to cost analysis must be done for this purpose.

For the economic analysis, the cost of the automatic switch is taken as $30,000 (IntelliRupter market value price) [19]. The interruption cost varies depending on the type of customers. Table 7.4 lists the interruption cost for all type of customers for an hour according to a survey report of The Midwest Independent Transmission System Operator [22].

Table 7.4 Interruption Cost per Kwh for Industrial, Commercial and Residential Load

Type of Customer	Interruption Cost (per kWh)
Industrial	\$500-\$600
Commercial	\$417
Residential	\$2

For different switch configurations, the interruption cost and total benefit is tabulated in Table 7.5. Case '0' is taken as a reference point. The total cost and benefits of partial and full automation will be compared with respect to this reference point for economic analysis.

Table 7.5 Total Interruption Cost and Benefit for the Residential Load

Case	Switch Configuration	Switch Cost (\$)	Interruption Cost (\$)	Total Cost (\$)	Benefit (\$)	ΔB/ΔC
0	MMAMMMA	60,000.00	10,656.00	70,656.00	-	
1	MMAAMMA	90,000.00	6,660.00	96,660.00	3,996.00	0.041
2	AMAAMMA	120,000.00	4,791.00	124,791.00	5,865.00	0.046
3	AAAAMMA	150,000.00	3,474.00	153,474.00	7,182.00	0.046
4	AAAAAMA	180,000.00	2,664.00	182,664.00	7,992.00	0.043
5	AAAAAAA	210,000.00	2,664.00	212,664.00	7,992.00	0.037

Figure 7.3 shows the plot of benefit to cost analysis of the 12 kV residential feeder. The benefit considerably increased due to the increase in number of automatic switches. Then the significant benefit of automation decreased. For this case, the optimal number of switches is 2.

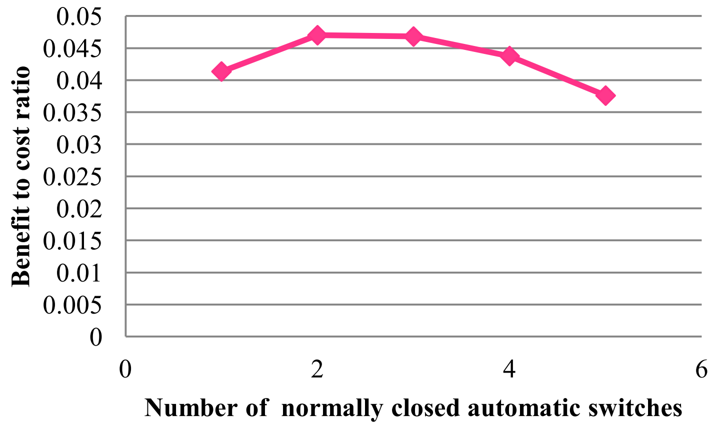

Figure 7.3 Benefit to Cost Analysis of 12 kV Residential Feeder

Case II: A 12 kV Parallel Commercial Feeder

Step I: In this case, Figure 7.1 is remodeled with the majority of the commercial load. Table 7.6 shows the network data of the commercial feeder. The load location and their individual consumption are shown in Table 7.7. Load point 7 is the industrial load of 2000 KW. Similarly, load points 5 and 6 are the residential load.

Table 7.6 Network Data of the Commercial Feeder

Failure Mode	Failure Rate (λ)	Total Length(miles)
A	0.15	4
B	0.15	4
C	0.15	4
D	0.15	4
E	0.15	4
F	0.15	4

Table 7.7 Load Data of the Commercial Feeder

Load Point	Avg No. of Customers	Avg Load (KW)
LP1	40	1600
LP2	40	1700
LP3	20	850
LP4	40	1800
LP5	40	300
LP6	25	200
LP7	5	2000

Step II: Reliability Analysis

All the assumptions made for reliability analysis are the same as that for the residential feeder. Appendix B.7 lists the reliability indices of the system for all possible placements for normally closed automatic switches. Table 7.8 lists the configuration of normally closed switches with the respective number of automatic switches for the best value of reliability. Figure 7.4 shows the plot of SAIFI and SAIDI improve as a result of an increase in automatic switches.

Table 7.8 Reliability Indices for number of Automatic Switches in the Commercial Feeder

No of automatic switch	Switch configuration	SAIFI	SAIDI	CMI
0	MMAMMMA	0.88	61.71	12960
1	MMAAMMA	0.44	38.57	8100
2	AMAAMMA	0.31	27.42	5760
3	AAAAMMA	0.24	20.57	4320
4	AAAAAMA	0.16	15.42	3240
5	AAAAAAA	0.14	15.42	3240

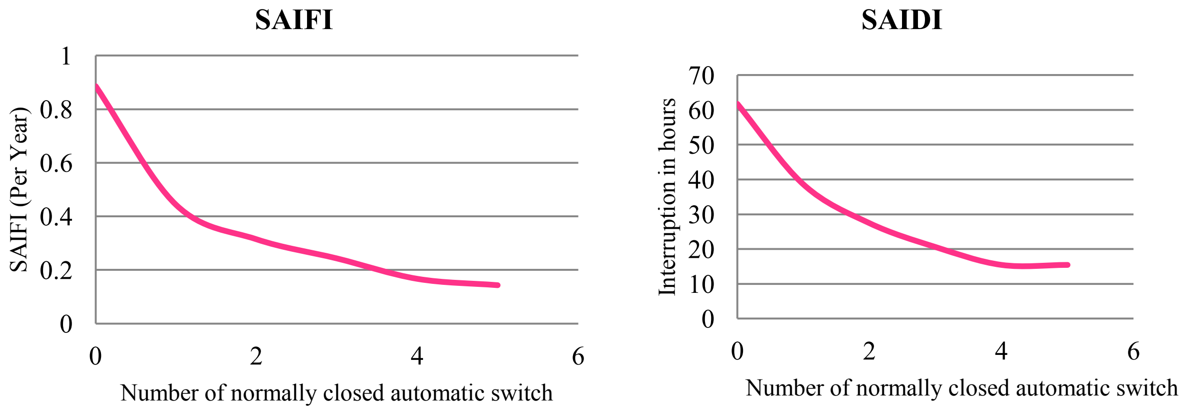

Figure 7.4 SAIFI and SAIDI Diagrams for 12 kV Commercial Feeder

Step III: Economic Analysis

For the economic analysis, all the assumptions made are the same as those for the residential feeder. The interruption rates are also the same as in Table 7.4. The total benefit and cost of different switch configuration for the commercial feeder is shown in Table 7.9

Table 7.9 Total Interruption Cost and Benefit for the Commercial Load

Case	Switch Configuration	Switch Cost ($)	Interruption Cost ($)	Total Cost ($)	Benefit ($)	ΔB/ΔC
0	MMAMMMA	60,000.00	2,978,100.00	3,038,100.00	-	
1	MMAAMMA	90,000.00	1,861,312.50	1,951,312.50	1,116,787.50	0.57
2	AMAAMMA	120,000.00	1,176,390.00	1,296,390.00	1,801,710.00	1.38
3	AAAAMMA	150,000.00	744,795.00	894,795.00	2,233,305.00	2.49
4	AAAAAMA	180,000.00	744,525.00	924,525.00	2,233,575.00	2.41
5	AAAAAAA	210,000.00	744,525.00	954,525.00	2,233,575.00	2.33

Figure 7.5 shows the cost to benefit analysis of the 12 kV commercial feeder. The benefits due to automation are significantly higher than as compared to the residential feeder. For

the commercial feeder, the optimal number of switches is 3 as the benefit to cost ratio starts to decrease after this point.

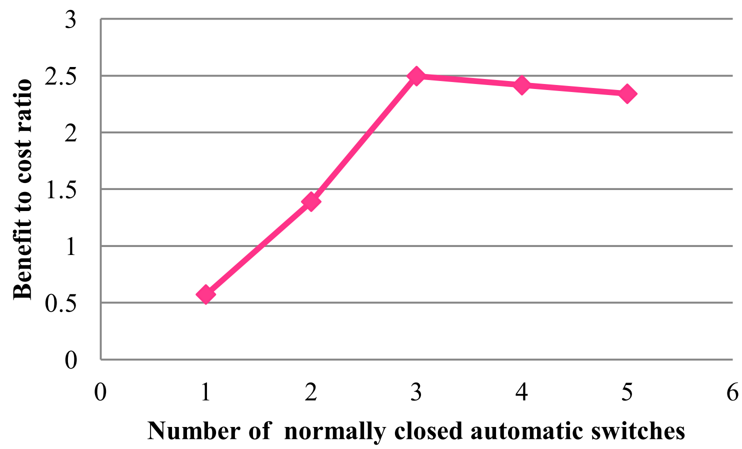

Figure 7.5 Benefit to Cost Analysis of 12 kV Commercial Feeder

Case III: A 12 kV Parallel Industrial Feeder

Step I: Figure 7.1 is modified again with the majority of the industrial load. Table 7.10 shows the network data of the industrial feeder. The load location and their individual consumption are shown in Table 7.11. Load point 1 is the residential loads with consumption 144 KW. Similarly, load points 6 and 7 are the commercial loads.

Table 7.10 Network Data of the Industrial Feeder

Failure Mode	Failure Rate (λ)	Total Length(miles)
A	0.15	4
B	0.15	4
C	0.15	4
D	0.15	4
E	0.15	4
F	0.15	4

Table 7.11 Load Data of the Industrial Feeder

Load Point	Avg No. of Customers	Avg Load (KW)
LP1	20	144
LP2	5	2500
LP3	5	4500
LP4	1	2000
LP5	5	2500
LP6	5	200
LP7	5	450

Step II: Reliability Analysis

Again, all the assumptions made for reliability analysis are the same as those for the residential feeder. Appendix C.7 lists the reliability indices of the system for all possible placements for normally closed automatic switches. Table 7.12 lists the configuration of normally closed switches with the respective number of automatic switches for the best value of reliability.

Table 7.12 Reliability Indices for number of Automatic Switches in the Industrial Feeder

No of Automatic Switch	Switch Configuration	SAIFI	SAIDI	CMI
0	MMAMMMA	0.782609	56.34783	2592
1	MAAMMMA	0.652174	44.41304	2043
2	MAAAMMA	0.26087	27.19565	1251
3	AAAAMMA	0.195652	17.02174	783
4	AAAAAMA	0.108696	14.08696	648
5	AAAAAAA	0.065217	14.08696	648

Figure 7.5 shows the plot of SAIFI and SAIDI improve as a result of an increase in automatic switches.

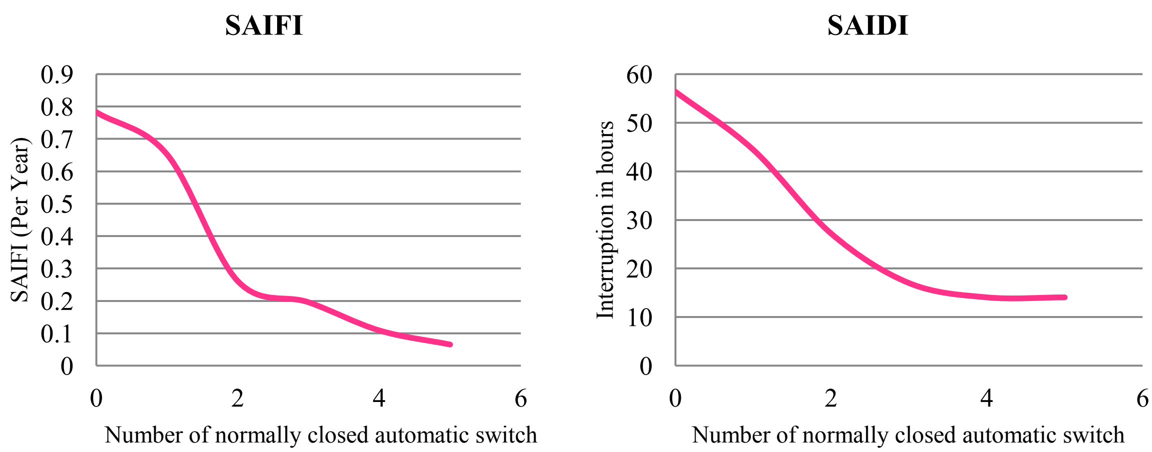

Figure 7.6 SAIFI and SAIDI Diagrams for 12 kV Industrial Feeder

Step III: Economic Analysis

For the economic analysis, again all the assumptions made are the same as those for the residential feeder. The interruption rates are mentioned in table 7.4. The total benefit and cost of different switch configuration for industrial feeder is shown in table 7.13

Table 7.13 Total Interruption Cost and Benefit for the Industrial Load

Case	Switch Configuration	Switch Cost($)	Interruption Cost($)	Total Cost ($)	Benefit ($)	ΔB/ΔC
0	MM**A**MMM**A**	60,000.00	7,740,345.60	7,800,345.6	0	-
1	MA**A**MMM**A**	90,000.00	4,837,716.00	4,927,716.00	2,92,629.60	0.58
2	AA**A**AMM**A**	120,000.00	3,420,172.80	3,540,172.80	4,320,172.80	1.22
3	AA**A**AMM**A**	150,000.00	2,610,086.40	2,760,086.40	5,130,259.20	1.85
4	AA**A**AAM**A**	180,000.00	1,935,086.40	2,115,086.40	5,805,259.20	2.74
5	AA**A**AAA**A**	210,000.00	1,935,086.40	2,145,086.40	5,805,259.20	2.70

As shown in Table 7.13, the benefits due to automation are significantly higher as compared to commercial as well as residential feeder. Figure 7.7 shows the benefit to cost ratio for the industrial feeder. The optimal number of automatic switches for the industrial customer is 4.

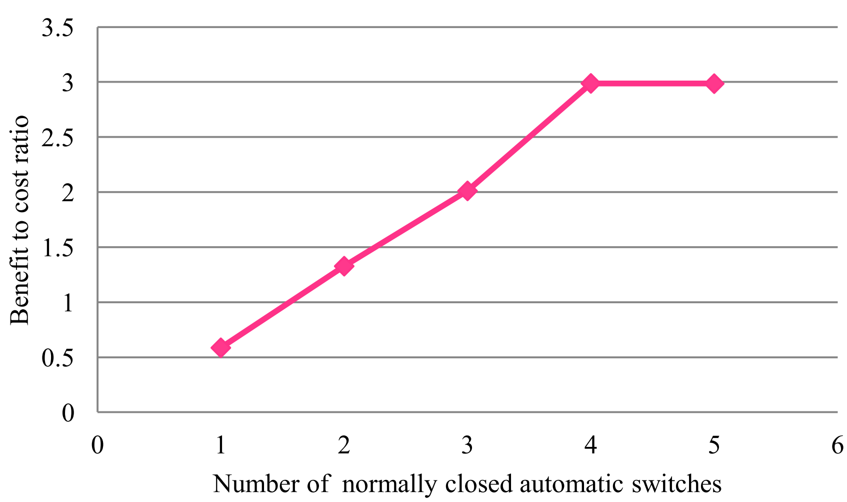

Figure 7.7 Benefit to Cost Analysis of 12 kV Industrial Feeder

CHAPTER VIII

DISCUSSION AND CONCLUSION

This chapter discusses the findings of the case studies and the conclusion drawn by comparing each model. Also, it briefly discusses the future implementation of the project.

Objectives of the Study

The main objective of the study is the reliability assessment of the automated distribution system and to propose the optimum number and location of automatic switches that improve reliability of the distribution system. A very simple analytical method has been implemented for the system analysis. This research aims to help the manager and reliability engineers of the utility company to understand the benefits and to perform economic analysis of the automation system.

Summary of the Findings

From the case studies conducted for residential, commercial and industrial feeders, the following conclusions can be drawn.

a. The reliability of the system improves as the automation increases for all kinds of load until a certain number of automatic switches are installed. After that, it saturates, i.e. no more reliability improvement with further automation.

b. Benefit of automation is less for the residential load as compared to industrial and commercial loads. This might be because the average consumption of the residential load is very small compared to commercial and industrial loads even though they are large in numbers. Figure 8.1 shows the comparison of benefit to cost ratio for residential, industrial and commercial types of customers.

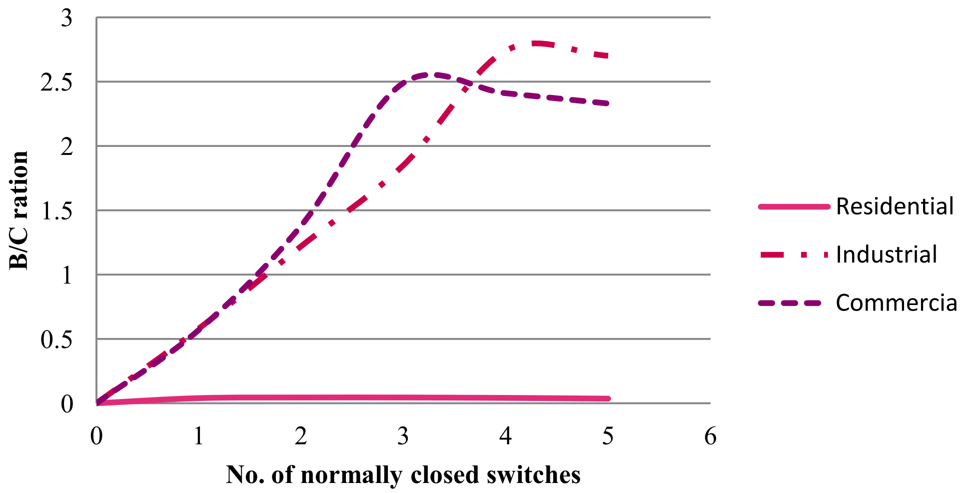

Figure 8.1 Comparison of Benefit to Cost Ratio of Industrial, Commercial and Residential Load

c. The number of automatic switches greatly depends upon the type of feeder. The number of automatic switches is higher for industrial and commercial customers as compared to the residential load. It may be due to the large interruption cost for the industrial and commercial customers. Therefore, the utility companies are very concerned to provide these kinds of customer a very reliable power supply at any cost. Generally big industries have multiple feeders as they share the portion of reliability improvement with the utility company.

d. Reliability of the distribution system greatly depends upon the placement of automatic switches. The reliability indices for different numbers of automatic switches for all types of feeders are shown in appendix A.7, B.7 and C.7. The reliability and benefits are different for various switch locations even though the number of automatic switches is the same.

Recommendations for Future Study

This thesis proposes a very simple analytical method for reliability assessment and system economic analysis using an excel spreadsheet. However, this method can be very time consuming if the number of load points are too high. In that case, simulation based methods can be used to find optimal placement of automatic switches. Also, for the reliability evaluation, this thesis accounts on the historic average data made available by utility companies. This model can be further enhanced to real time data using Opal RT. Furthermore, the reliability and economic analysis of the system with integration of DG (Distributed Generation) can be carried out.

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APPENDIX A

RELIABILITY ASSESSMENT AND ECONOMIC ANALYSIS OF THE RESIDENTIAL FEEDER

Table A.1 Switch Placement Module for the Residential Feeder

Switch position	Type	Switching time	MTTR
1	1	0.001388889	2
2	1	0.001388889	2
3	1	0.001388889	2
4	1	0.001388889	2
5	1	0.001388889	2
6	1	0.001388889	2
7	1	0.001388889	2
No. of Automatic switch	**7**		

**1=Automatic, 0=Manual, Automatic Switching time =5 sec= 0.001388889 hr

Table A.2 Reliability Indices for Switch Module shown in Table A.1

SAIFI (INT/CUST)	**0.144204852**
SAIDI (min/CUST INT)	**14.5309973**
CAIDI(min/Int)	**100.7663551**
ASAI	**0.99834121**
CMI	**10782**
Interruption cost	**$ 2,664.00**

Table A.3 Power availability Rate for all Load Points Depending upon Switch Module shown in A.1 using FMEA Method for the Residential Feeder

Fault	Load point (LP1)			Load point (LP2)			Load point (LP3)			Load point (LP4)			Load point (LP5)			Load point (LP6)			Load point (LP7)		
	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)
A	**0.15**	2	**0.3**	**0.15**	0.0013888889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
B	**0.15**	0.001388889	**0**	**0.15**	2	**0.3**	**0.15**	0.001388889	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
C	**0.15**	0.001388889	**0**	**0.15**	0.0013888889	**0**	**0.15**	2	**0.3**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
D	**0.15**	0.001388889	**0**	**0.15**	0.0013888889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
E	**0.15**	0.001388889	**0**	**0.15**	0.0013888889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**
F	**0.15**	0.001388889	**0**	**0.15**	0.0013888889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	2	**0.3**
Σλ	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**

Table A.4 Number of Customer Interruption for different Failure Modes Depending on Switch Module shown in A.1

Components	**Failure rate (λ/yr)**	**Total No of customer interrupted**	**Customer Interruption (CI)**	**Avg no of momentary interruption**	**Cust Momentary Interruption**
A	0.15	133	19	609	91
B	0.15	200	30	542	81
C	0.15	133	19	609	91
D	0.15	133	19	609	91
E	0.15	133	19	609	91
F	0.15	10	1	732	109
			107		554

Table A.5 Customer Minute Interruption for all Load Points in the Residential Feeder

Load Point	Avg No. of Customers (N)	U(λ.r)	CMI (N*U*60 min)
LP1	**133**	**0.3**	**2394**
LP2	**100**	**0.3**	**1800**
LP3	**133**	**0.3**	**2394**
LP4	**100**	**0.3**	**1800**
LP5	**133**	**0.3**	**2394**
LP6	**133**	**0.3**	**2394**
LP7	**10**	**0.3**	**180**
			10782

Table A.6 Customer Interruption Cost for Different Loads Depending on their Rates

Load Point	Interruption cost rate ($/kWhr)	Avg. Load (kW)	Interruption rate (hr/yr)	Interruption cost ($)
LP1	2	900	0.3	$ 540.00
LP2	2	850	0.3	$ 510.00
LP3	2	900	0.3	$ 540.00
LP4	2	890	0.3	$ 534.00
LP5	2	900	0.3	$ 540.00
LP6	2	700	0.3	$ 420.00
LP7	417	450	0.3	$ 56,295.00
			Total Interruption cost	**$ 2,664.00**

Table A.7 Detail Reliability and Economic Analysis Sorted based on B/C Ratio for Different Number and Switch Locations for the Residential Feeder

No. of NC automatic Sv	S1	S2	S3	S4	S5	S6	S7	SAIFI	SAIDI	CMI	Switch Cost	INTERRUPTION COST	Total Cost	Benefit	ΔB/ΔC	CMI savings	$/CMI Savings
0	0	0	1	0	0	0	1	0.897574	58.12399	43128	$ 60,000.00	$ 10,656.00	$ 70,656.00	$ -			
1	0	0	1	0	0	1	1	0.735849	50.85849	37737	$ 90,000.00	$ 9,324.00	$ 99,324.00	$ 1,332.00	0.013410656	5391	$ 18.42
1	0	0	1	0	1	0	1	0.536388	43.59299	32346	$ 90,000.00	$ 7,992.00	$ 97,992.00	$ 2,664.00	0.027185893	10782	$ 9.09
1	0	1	1	0	0	0	1	0.638814	42.79245	31752	$ 90,000.00	$ 7,974.00	$ 97,974.00	$ 2,682.00	0.02737461	11376	$ 8.61
1	1	0	1	0	0	0	1	0.638814	42.79245	31752	$ 90,000.00	$ 7,974.00	$ 97,974.00	$ 2,682.00	0.02737461	11376	$ 8.61
1	0	0	1	1	0	0	1	0.444744	36.32749	26955	$ 90,000.00	$ 6,660.00	$ 96,660.00	$ 3,996.00	0.041340782	16173	$ 5.98
2	0	0	1	0	1	1	1	0.506739	43.59299	32346	$ 120,000.00	$ 7,992.00	$ 127,992.00	$ 2,664.00	0.020813801	10782	$ 11.87
2	0	1	1	0	0	1	1	0.506739	37.14016	27558	$ 120,000.00	$ 6,912.00	$ 126,912.00	$ 3,744.00	0.029500756	15570	$ 8.15
2	1	0	1	0	0	1	1	0.506739	37.14016	27558	$ 120,000.00	$ 6,912.00	$ 126,912.00	$ 3,744.00	0.029500756	15570	$ 8.15
2	0	0	1	1	0	1	1	0.385445	34.71429	25758	$ 120,000.00	$ 6,390.00	$ 126,390.00	$ 4,266.00	0.03375267	17370	$ 7.28
2	0	0	1	1	1	0	1	0.361186	31.48787	23364	$ 120,000.00	$ 5,850.00	$ 125,850.00	$ 4,806.00	0.038188319	19764	$ 6.37
2	0	1	1	0	1	0	1	0.361186	31.48787	23364	$ 120,000.00	$ 5,850.00	$ 125,850.00	$ 4,806.00	0.038188319	19764	$ 6.37
2	1	0	1	0	1	0	1	0.361186	31.48787	23364	$ 120,000.00	$ 5,850.00	$ 125,850.00	$ 4,806.00	0.038188319	19764	$ 6.37
2	1	1	1	0	0	0	1	0.433962	29.47439	21870	$ 120,000.00	$ 5,577.00	$ 125,577.00	$ 5,079.00	0.040445304	21258	$ 5.91
2	0	1	1	1	0	0	1	0.32345	27.44879	20367	$ 120,000.00	$ 5,058.00	$ 125,058.00	$ 5,598.00	0.04476323	22761	$ 5.49
2	1	0	1	1	0	0	1	0.32345	26.23585	19467	$ 120,000.00	$ 4,791.00	$ 124,791.00	$ 5,865.00	0.046998582	23661	$ 5.27
3	0	0	1	1	1	1	1	0.331536	31.48787	23364	$ 150,000.00	$ 5,850.00	$ 155,850.00	$ 4,806.00	0.030837344	19764	$ 7.89
3	0	1	1	0	1	1	1	0.331536	31.48787	23364	$ 150,000.00	$ 5,850.00	$ 155,850.00	$ 4,806.00	0.030837344	19764	$ 7.89
3	1	0	1	0	1	1	1	0.331536	31.48787	23364	$ 150,000.00	$ 5,850.00	$ 155,850.00	$ 4,806.00	0.030837344	19764	$ 7.89
3	0	1	1	1	0	1	1	0.264151	25.83558	19170	$ 150,000.00	$ 4,788.00	$ 154,788.00	$ 5,868.00	0.037909915	23958	$ 6.46
3	1	1	1	0	0	1	1	0.331536	25.43531	18873	$ 150,000.00	$ 4,785.00	$ 154,785.00	$ 5,871.00	0.037930032	24255	$ 6.38
3	1	0	1	1	0	1	1	0.264151	24.62264	18270	$ 150,000.00	$ 4,521.00	$ 154,521.00	$ 6,135.00	0.039703341	24858	$ 6.22
3	0	1	1	1	1	0	1	0.239892	22.60916	16776	$ 150,000.00	$ 4,248.00	$ 154,248.00	$ 6,408.00	0.041543488	26352	$ 5.85
3	1	1	1	0	1	0	1	0.239892	21.39623	15876	$ 150,000.00	$ 3,993.00	$ 153,993.00	$ 6,663.00	0.043268201	27252	$ 5.65
3	1	0	1	1	1	0	1	0.239892	21.39623	15876	$ 150,000.00	$ 3,981.00	$ 153,981.00	$ 6,675.00	0.043349504	27252	$ 5.65
3	1	1	1	1	0	0	1	0.257412	19.37062	14373	$ 150,000.00	$ 3,474.00	$ 153,474.00	$ 7,182.00	0.0467962	28755	$ 5.34
4	0	1	1	1	1	1	1	0.210243	22.60916	16776	$ 180,000.00	$ 4,248.00	$ 184,248.00	$ 6,408.00	0.034779211	26352	$ 6.99
4	1	1	1	0	1	1	1	0.210243	21.39623	15876	$ 180,000.00	$ 3,993.00	$ 183,993.00	$ 6,663.00	0.036213334	27252	$ 6.75
4	1	0	1	1	1	1	1	0.210243	21.39623	15876	$ 180,000.00	$ 3,981.00	$ 183,981.00	$ 6,675.00	0.03628092	27252	$ 6.75
4	1	1	1	1	0	1	1	0.198113	17.75741	13176	$ 180,000.00	$ 3,204.00	$ 183,204.00	$ 7,452.00	0.040675968	29952	$ 6.12
4	1	1	1	1	1	0	1	0.173854	14.531	10782	$ 180,000.00	$ 2,664.00	$ 182,664.00	$ 7,992.00	0.043752464	32346	$ 5.65
5	1	1	1	1	1	1	1	0.144205	14.531	10782	$ 210,000.00	$ 2,664.00	$ 212,664.00	$ 7,992.00	0.037580409	32346	$ 6.57

APPENDIX B

RELIABILITY ASSESSMENT AND ECONOMIC ANALYSIS OF THE COMMERCIAL FEEDER

Table B.1 Switch Placement Module for the Commercial Feeder

Switch position	Type	Switching time	MTTR
1	1	0.001388889	2
2	1	0.001388889	2
3	1	0.001388889	2
4	1	0.001388889	2
5	1	0.001388889	2
6	1	0.001388889	2
7	1	0.001388889	2
No. of Automatic switch	**7**		

**1=Automatic, 0=Manual, Automatic Switching time =5 sec= 0.001388889 hr

Table B.2 Reliability Indices for Switch Module Shown in Table B.1

SAIFI (INT/CUST)	**0.142857143**
SAIDI (min/CUST INT)	**15.42857143**
CAIDI(min/Int)	**108**
ASAI	**0.998238748**
CMI	**3240**
Interruption cost	**$ 744,525.00**

Table B.3 Power Availability Rate for all Load Points Depending upon Switch Module shown in B.1 using FMEA Method for the Commercial Feeder

Fault	**Load point (LP1)**			**Load point (LP2)**			**Load point (LP3)**			**Load point (LP4)**			**Load point (LP5)**			**Load point (LP6)**			**Load point (LP7)**		
	λ (f/yr)	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**	**λ (f/yr)**	**r (hr)**	**U=λ.r (hr/yr)**
A	**0.15**	2	**0.3**	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
B	**0.15**	0.001388889	**0**	**0.15**	2	**0.3**	**0.15**	0.001388889	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
C	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	2	**0.3**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
D	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**
E	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	2	**0.3**	**0.15**	0.001389	**0**
F	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.001388889	**0**	**0.15**	0.00138889	**0**	**0.15**	0.001389	**0**	**0.15**	0.001389	**0**	**0.15**	2	**0.3**
∑λ	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**	**0.9**		**0.3**

Table B.4 Number of Customer Interruption for different failure modes depending on switch module shown in B.1

Number of customers	**A**	**B**	**C**	**D**	**E**	**F**
40	2	0.001388889	0.001388889	0.001388889	0.001388889	0.001388889
40	0.001388889	2	0.001388889	0.001388889	0.001388889	0.001388889
20	0.001388889	0.001388889	2	0.001388889	0.001388889	0.001388889
40	0.001388889	2	0.001388889	0.001388889	0.001388889	0.001388889
40	0.001388889	0.001388889	0.001388889	2	0.001388889	0.001388889
25	0.001388889	0.001388889	0.001388889	0.001388889	2	0.001388889
5	0.001388889	0.001388889	0.001388889	0.001388889	0.001388889	2
Average load affected	**40**	**80**	**20**	**40**	**25**	**5**

Table B.5 Customer Minute Interruption for all Load Points in the Commercial Feeder

Faults	Failure rate (λ/yr)	Avg. No of customer interrupted	Customer Interruption (CI)	Avg no of momentary interruption	Cust Momentary Interruption
A	0.15	40	6	170	25
B	0.15	80	12	130	19
C	0.15	20	3	190	28
D	0.15	40	6	170	25
E	0.15	25	3	185	27
F	0.15	5	0	205	30
			30		154

Table B.6 Customer Interruption Cost for Different Loads Depending their Rates

Load Point	Interruption cost rate ($/kWhr)	Avg. Load (kW)	Interruption rate (hr/yr)	Interruption cost ($)
LP1	417	1600	0.3	$ 200,160.00
LP2	417	1700	0.3	$ 212,670.00
LP3	417	850	0.3	$ 106,335.00
LP4	417	1800	0.3	$ 225,180.00
LP5	2	300	0.3	$ 180.00
LP6	2	200	0.3	$ 120.00
LP7	45	2000	0.3	$ 27,000.00
			Total Interruption cost	**$ 744,525.00**

Table B.7 Detail Reliability and Economic Analysis Sorted based on B/C Ratio For Different Number and Switch Locations for the Commercial Feeder

No. of NC Aut switch	S1	S2	S3	S4	S5	S6	S7	SAIFI	SAIDI	CMI	Switch Cost	INTERRUPTION COST	Total Cost	Benefit	ΔB/ΔC	CMI savings	$/CMI Savings
0	0	0	1	0	0	0	1	0.885714	61.71429	12960	$ 60,000.00	$ 2,978,100.00	$ 3,038,100.00	$ -			
1	0	0	1	0	0	1	1	0.714286	54	11340	$ 90,000.00	$ 2,605,837.50	$ 2,695,837.50	$ 372,262.50	0.138087885	1620	$ 1,664.10
1	0	1	1	0	0	0	1	0.680952	49.71429	10440	$ 90,000.00	$ 2,340,000.00	$ 2,430,000.00	$ 638,100.00	0.262592593	2520	$ 964.29
1	0	0	1	0	1	0	1	0.552381	46.28571	9720	$ 90,000.00	$ 2,233,575.00	$ 2,323,575.00	$ 744,525.00	0.320422194	3240	$ 717.15
1	1	0	1	0	0	0	1	0.62381	45.42857	9540	$ 90,000.00	$ 2,105,437.50	$ 2,195,437.50	$ 872,662.50	0.397489111	3420	$ 641.94
1	0	0	1	1	0	0	1	0.442857	38.57143	8100	$ 90,000.00	$ 1,861,312.50	$ 1,951,312.50	$ 1,116,787.50	0.572326319	4860	$ 401.50
2	0	0	1	0	1	1	1	0.528571	46.28571	9720	$ 120,000.00	$ 2,233,575.00	$ 2,353,575.00	$ 744,525.00	0.316337911	3240	$ 726.41
2	0	1	1	0	0	1	1	0.528571	42.85714	9000	$ 120,000.00	$ 2,020,905.00	$ 2,140,905.00	$ 957,195.00	0.447098307	3960	$ 540.63
2	0	0	1	1	0	1	1	0.385714	36.85714	7740	$ 120,000.00	$ 1,861,222.50	$ 1,981,222.50	$ 1,116,877.50	0.563731484	5220	$ 379.54
2	0	0	1	1	1	0	1	0.366667	33.42857	7020	$ 120,000.00	$ 1,861,042.50	$ 1,981,042.50	$ 1,117,057.50	0.563873567	5940	$ 333.51
2	1	0	1	0	0	1	1	0.485714	39.42857	8280	$ 120,000.00	$ 1,833,255.00	$ 1,953,255.00	$ 1,144,845.00	0.586121628	4680	$ 417.36
2	0	1	1	0	1	0	1	0.395238	36	7560	$ 120,000.00	$ 1,701,810.00	$ 1,821,810.00	$ 1,276,290.00	0.700561529	5400	$ 337.37
2	1	0	1	0	1	0	1	0.366667	33.42857	7020	$ 120,000.00	$ 1,561,072.50	$ 1,681,072.50	$ 1,417,027.50	0.842930629	5940	$ 283.01
2	1	1	1	0	0	0	1	0.461905	34.28571	7200	$ 120,000.00	$ 1,514,250.00	$ 1,634,250.00	$ 1,463,850.00	0.895731987	5760	$ 283.72
2	0	1	1	1	0	0	1	0.328571	30.85714	6480	$ 120,000.00	$ 1,382,805.00	$ 1,502,805.00	$ 1,595,295.00	1.061544911	6480	$ 231.91
2	1	0	1	1	0	0	1	0.314286	27.42857	5760	$ 120,000.00	$ 1,176,390.00	$ 1,296,390.00	$ 1,801,710.00	1.389790109	7200	$ 180.05
3	0	0	1	1	1	1	1	0.342857	33.42857	7020	$ 150,000.00	$ 1,861,042.50	$ 2,011,042.50	$ 1,117,057.50	0.555461906	5940	$ 338.56
3	0	1	1	0	1	1	1	0.371429	36	7560	$ 150,000.00	$ 1,701,810.00	$ 1,851,810.00	$ 1,276,290.00	0.689212176	5400	$ 342.93
3	1	0	1	0	1	1	1	0.342857	33.42857	7020	$ 150,000.00	$ 1,561,072.50	$ 1,711,072.50	$ 1,417,027.50	0.828151642	5940	$ 288.06
3	0	1	1	1	0	1	1	0.271429	29.14286	6120	$ 150,000.00	$ 1,382,715.00	$ 1,532,715.00	$ 1,595,385.00	1.040888228	6840	$ 224.08
3	0	1	1	1	1	0	1	0.252381	25.71429	5400	$ 150,000.00	$ 1,382,535.00	$ 1,532,535.00	$ 1,595,565.00	1.041127935	7560	$ 202.72
3	1	1	1	0	0	1	1	0.342857	29.14286	6120	$ 150,000.00	$ 1,295,235.00	$ 1,445,235.00	$ 1,682,865.00	1.164423087	6840	$ 211.29
3	1	0	1	1	0	1	1	0.257143	25.71429	5400	$ 150,000.00	$ 1,176,300.00	$ 1,326,300.00	$ 1,801,800.00	1.358516173	7560	$ 175.44
3	1	0	1	1	1	0	1	0.238095	22.28571	4680	$ 150,000.00	$ 1,176,120.00	$ 1,326,120.00	$ 1,801,980.00	1.358836304	8280	$ 160.16
3	1	1	1	0	1	0	1	0.252381	24	5040	$ 150,000.00	$ 1,076,220.00	$ 1,226,220.00	$ 1,901,880.00	1.551010422	7920	$ 154.83
3	1	1	1	1	0	0	1	0.242857	20.57143	4320	$ 150,000.00	$ 744,795.00	$ 894,795.00	$ 2,233,305.00	2.495884532	8640	$ 103.56
4	0	1	1	1	1	1	1	0.228571	25.71429	5400	$ 180,000.00	$ 1,382,535.00	$ 1,562,535.00	$ 1,595,565.00	1.021138726	7560	$ 206.68
4	1	0	1	1	1	1	1	0.214286	22.28571	4680	$ 180,000.00	$ 1,176,120.00	$ 1,356,120.00	$ 1,801,980.00	1.328776214	8280	$ 163.78
4	1	1	1	0	1	1	1	0.228571	24	5040	$ 180,000.00	$ 1,076,220.00	$ 1,256,220.00	$ 1,901,880.00	1.513970483	7920	$ 158.61
4	1	1	1	1	0	1	1	0.185714	18.85714	3960	$ 180,000.00	$ 744,705.00	$ 924,705.00	$ 2,233,395.00	2.41525135	9000	$ 102.75
4	1	1	1	1	1	0	1	0.166667	15.42857	3240	$ 180,000.00	$ 744,525.00	$ 924,525.00	$ 2,233,575.00	2.415916281	9720	$ 95.12
5	1	1	1	1	1	1	1	0.142857	15.42857	3240	$ 210,000.00	$ 744,525.00	$ 954,525.00	$ 2,233,575.00	2.339985857	9720	$ 98.20

APPENDIX C

RELIABILITY ASSESSMENT AND ECONOMIC ANALYSIS OF THE INDUSTRIAL FEEDER

Table C.1 Switch Placement Module for the Industrial Load

Switch position	Type	Switching time	MTTR
1	1	0.001388889	2
2	1	0.001388889	2
3	1	0.001388889	2
4	1	0.001388889	2
5	1	0.001388889	2
6	1	0.001388889	2
7	1	0.001388889	2
No. of Automatic switch	**7**		

**1=Automatic, 0=Manual, Automatic Switching time =5 sec= 0.001388889 hr

Table C.2 Reliability Indices for Switch Module shown in Table C.1

SAIFI (INT/CUST)	**0.065217391**
SAIDI (min/CUST INT)	**14.08695652**
CAIDI(min/Int)	**216**
ASAI	**0.9983919**
CMI	**648**
Interruption cost	**$ 1,935,086.40**

Table C.3 Power Availability Rate for all Load Points Depending upon Switch Module shown in C.1 using FMEA Method for the Industrial Feeder

Failure Component	Load point (LP1)			Load point (LP2)			Load point (LP3)			Load point (LP4)			Load point (LP5)			Load point (LP6)			Load point (LP7)		
	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)	λ (f/yr)	r (hr)	U=λ.r (hr/yr)
A	0.15	2	0.3	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0
B	0.15	5sec	0	0.15	2	0.3	0.15	5sec	0	0.15	2	0.3	0.15	0.001389	0	0.15	0.001389	0	0.15	5sec	0
C	0.15	5sec	0	0.15	5sec	0	0.15	2	0.3	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0
D	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	2	0.3	0.15	5sec	0	0.15	5sec	0
E	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	2	0.3	0.15	5sec	0
F	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	5sec	0	0.15	0.001389	0	0.15	5sec	0	0.15	2	0.3
∑λ	0.9		0.3	0.9		0.3	0.9		0.3	0.9		0.3	0.9		0.3	0.9		0.3	0.9		0.3

Table C.4 Number of Customer Interruption for Different Failure Modes Depending on Switch Module shown in C.1

Components	Failure rate (λ/yr)	Avg. No of customer interrupted	Customer Interruption (CI)	Avg no of momentary interruption	Cust Momentary Interruption
A	0.15	20	3	26	3
B	0.15	6	0	40	6
C	0.15	5	0	41	6
D	0.15	5	0	41	6
E	0.15	5	0	41	6
F	0.15	5	0	41	6
			3		33

Table C.5 Customer Minute Interruption for all Load Points in the Industrial Feeder

Load Point	Avg No. of Customers	U(λ.r)	CMI (Customer minute Interruption)
LP1	**20**	**0.3**	**360**
LP2	**5**	**0.3**	**90**
LP3	**5**	**0.3**	**90**
LP4	**1**	**0.3**	**18**
LP5	**5**	**0.3**	**90**
LP6	**5**	**0.3**	**90**
LP7	**5**	**0.3**	**90**
			648

Table C.6 Customer Interruption Cost for Different Loads Depending on their Rates

Load Point	Interruption cost rate ($/kWhr)	Avg. Load (kW)	Interruption rate (hr/yr)	Interruption cost ($)
LP1	2	144	0.3	$ 86.40
LP2	600	2500	0.3	$ 450,000.00
LP3	500	4500	0.3	$ 675,000.00
LP4	600	2000	0.3	$ 360,000.00
LP5	600	2500	0.3	$ 450,000.00
LP6	417	200	0.3	$ 25,020.00
LP7	417	450	0.3	$ 56,295.00
			Total Interruption cost	**$ 1,935,086.40**

Table C.7 Detail Reliability and Economic Analysis Sorted based on B/C Ratio For Different Number and Switch Locations for the Industrial Feeder

No. of NC Automated Switches	S1	S2	S3	S4	S5	S6	S7	SAIFI	SAIDI	CMI	Switch Cost	INTERRUPTION COST	Total Cost	Benefit	ΔB/ΔC	CMI savings	$/CMI Savings
0	0	0	1	0	0	0	1	0.782609	56.34783	2592	$ 60,000.00	$ 7,740,345.60	$ 7,800,345.60	$ -			
1	0	0	1	0	0	1	1	0.652174	49.30435	2268	$ 90,000.00	$ 6,772,802.40	$ 6,862,802.40	$ 967,543.20	0.140983689	324	$ 21,181.49
1	1	0	1	0	0	0	1	0.391304	29.73913	1368	$ 90,000.00	$ 6,772,586.40	$ 6,862,586.40	$ 967,759.20	0.141019602	1224	$ 5,606.69
1	0	0	1	0	1	0	1	0.478261	42.26087	1944	$ 90,000.00	$ 5,805,259.20	$ 5,895,259.20	$ 1,935,086.40	0.328244499	648	$ 9,097.62
1	0	1	1	0	0	0	1	0.652174	44.41304	2043	$ 90,000.00	$ 5,085,302.40	$ 5,175,302.40	$ 2,655,043.20	0.513021848	549	$ 9,426.78
1	0	0	1	1	0	0	1	0.391304	35.21739	1620	$ 90,000.00	$ 4,837,716.00	$ 4,927,716.00	$ 2,902,629.60	0.589041576	972	$ 5,069.67
2	0	0	1	0	1	1	1	0.434783	42.26087	1944	$ 120,000.00	$ 5,805,259.20	$ 5,925,259.20	$ 1,935,086.40	0.326582574	648	$ 9,143.92
2	1	0	1	0	0	1	1	0.326087	26.6087	1224	$ 120,000.00	$ 5,805,086.40	$ 5,925,086.40	$ 1,935,259.20	0.326621262	1368	$ 4,331.20
2	1	0	1	0	1	0	1	0.23913	23.47826	1080	$ 120,000.00	$ 4,837,586.40	$ 4,957,586.40	$ 2,902,759.20	0.585518631	1512	$ 3,278.83
2	0	0	1	1	0	1	1	0.304348	34.23913	1575	$ 120,000.00	$ 4,612,716.00	$ 4,732,716.00	$ 3,127,629.60	0.660853007	1017	$ 4,653.60
2	0	1	1	0	0	1	1	0.434783	38.34783	1764	$ 120,000.00	$ 4,455,259.20	$ 4,575,259.20	$ 3,285,086.40	0.718010993	828	$ 5,525.68
2	1	1	1	0	0	0	1	0.326087	21.71739	999	$ 120,000.00	$ 4,230,086.40	$ 4,350,086.40	$ 3,510,259.20	0.80694011	1593	$ 2,730.75
2	0	0	1	1	1	0	1	0.304348	32.28261	1485	$ 120,000.00	$ 4,162,716.00	$ 4,282,716.00	$ 3,577,629.60	0.835364661	1107	$ 3,868.76
2	1	0	1	1	0	0	1	0.23913	21.13043	972	$ 120,000.00	$ 3,915,086.40	$ 4,035,086.40	$ 3,825,259.20	0.947999329	1620	$ 2,490.79
2	0	1	1	0	1	0	1	0.304348	32.28261	1485	$ 120,000.00	$ 3,825,216.00	$ 3,945,216.00	$ 3,915,129.60	0.992373954	1107	$ 3,563.88
2	0	1	1	1	0	0	1	0.26087	27.19565	1251	$ 120,000.00	$ 3,420,172.80	$ 3,540,172.80	$ 4,320,172.80	1.220328228	1341	$ 2,639.95
3	1	0	1	0	1	1	1	0.195652	23.47826	1080	$ 150,000.00	$ 4,837,586.40	$ 4,987,586.40	$ 2,902,759.20	0.581996775	1512	$ 3,298.67
3	0	0	1	1	1	1	1	0.26087	32.28261	1485	$ 150,000.00	$ 4,162,716.00	$ 4,312,716.00	$ 3,577,629.60	0.82955372	1107	$ 3,895.86
3	0	1	1	0	1	1	1	0.26087	32.28261	1485	$ 150,000.00	$ 3,825,216.00	$ 3,975,216.00	$ 3,915,129.60	0.984884746	1107	$ 3,590.98
3	1	0	1	1	0	1	1	0.152174	20.15217	927	$ 150,000.00	$ 3,690,086.40	$ 3,840,086.40	$ 4,050,259.20	1.054731269	1665	$ 2,306.36
3	1	1	1	0	0	1	1	0.195652	19.56522	900	$ 150,000.00	$ 3,600,086.40	$ 3,750,086.40	$ 4,140,259.20	1.104043683	1692	$ 2,216.36
3	1	0	1	1	1	0	1	0.152174	18.19565	837	$ 150,000.00	$ 3,240,086.40	$ 3,390,086.40	$ 4,500,259.20	1.327476255	1755	$ 1,931.67
3	0	1	1	1	0	1	1	0.173913	26.21739	1206	$ 150,000.00	$ 3,195,172.80	$ 3,345,172.80	$ 4,545,172.80	1.358725863	1386	$ 2,413.54
3	1	1	1	0	1	0	1	0.152174	17.41304	801	$ 150,000.00	$ 2,970,086.40	$ 3,120,086.40	$ 4,770,259.20	1.528886892	1791	$ 1,742.09
3	0	1	1	1	1	0	1	0.173913	24.26087	1116	$ 150,000.00	$ 2,745,172.80	$ 2,895,172.80	$ 4,995,172.80	1.725345306	1476	$ 1,961.50
3	1	1	1	1	0	0	1	0.195652	17.02174	783	$ 150,000.00	$ 2,610,086.40	$ 2,760,086.40	$ 5,130,259.20	1.858731379	1809	$ 1,525.75
4	1	0	1	1	1	1	1	0.108696	18.19565	837	$ 180,000.00	$ 3,240,086.40	$ 3,420,086.40	$ 4,500,259.20	1.315832021	1755	$ 1,948.77
4	1	1	1	0	1	1	1	0.108696	17.41304	801	$ 180,000.00	$ 2,970,086.40	$ 3,150,086.40	$ 4,770,259.20	1.514326464	1791	$ 1,758.84
4	0	1	1	1	1	1	1	0.130435	24.26087	1116	$ 180,000.00	$ 2,745,172.80	$ 2,925,172.80	$ 4,995,172.80	1.707650502	1476	$ 1,981.82
4	1	1	1	1	0	1	1	0.108696	16.04348	738	$ 180,000.00	$ 2,385,086.40	$ 2,565,086.40	$ 5,355,259.20	2.087750027	1854	$ 1,383.54
4	1	1	1	1	1	0	1	0.108696	14.08696	648	$ 180,000.00	$ 1,935,086.40	$ 2,115,086.40	$ 5,805,259.20	2.744691281	1944	$ 1,088.01
5	1	1	1	1	1	1	1	0.065217	14.08696	648	$ 210,000.00	$ 1,935,086.40	$ 2,145,086.40	$ 5,805,259.20	2.706305536	1944	$ 1,103.44

VITA

Sudip Manandhar was born in Kathmandu, Nepal. He completed his Bachelor's Degree in Electrical Engineering with major in Power Systems from the Institute of Engineering, Pulchowk Campus, Nepal. He then immigrated to California, USA in order to pursue his Master's Degree in Business Administration in 2008. In 2011, Sudip accepted a graduate assistantship in the Department of Electrical Engineering at the University of Tennessee at Chattanooga and completed his Master's Degree in Electrical Engineering majoring in Power Systems in May, 2013. Sudip has one sibling.